DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

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COST AND FEASIBILITY OF STANDARD ELECTRIC WINCH DRIVE

by

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MOBILE SUPPORT SYSTEMS GROUP

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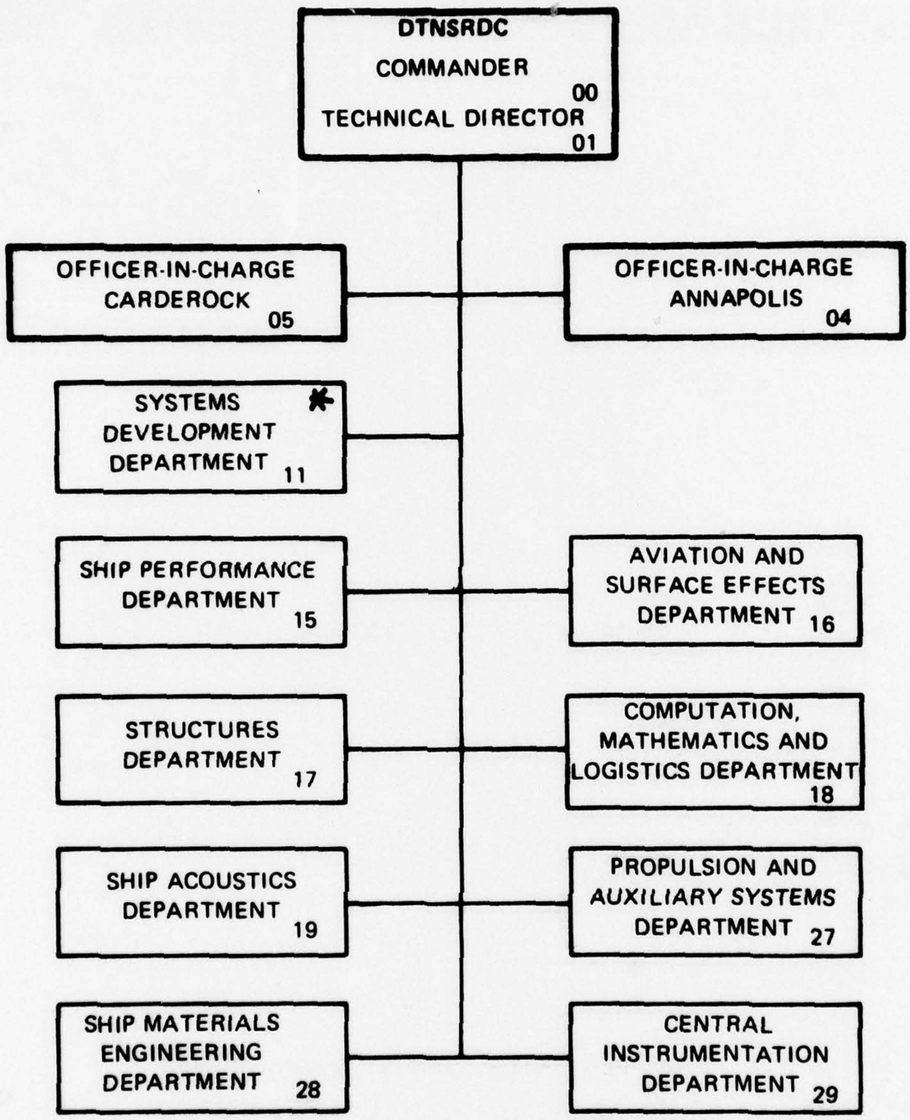

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system. The latter type is further broken down into Voltage Source, Current Source, and Pulse Width Modulation systems. Each is described and their principal features, availability, and reliability/maintainability are discussed. The DC System uses a motor that is larger, more complex, and less reliable than the AC System. With the requirement for regenerative operation, the DC and AC Systems controllers are quite similar in design complexity and number of components. The Current Source/Slip Regulated AC Drive System is concluded to be superior for winch service since it best satisfies the critical regeneration and overload requirements, and uses the most rugged and reliable drive motor.

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ABSTRACT

The cost and feasibility of electric winch drives for underway replenishment highline/spanwire winches is investigated. The winch drives of interest are those using Silicon Controlled Rectifier (SCR) solid state motor controls. Service requirements including performance parameters and reliability/maintainability requirements are identified. Candidate electric drive systems are the DC Motor/Controller system and the AC Motor/Controller system. The latter type is further broken down into Voltage Source, Current Source, and Pulse Width Modulation systems. Each is described and their principal features, availability, and reliability/maintainability are discussed. The DC System uses a motor that is larger, more complex, and less reliable than the AC System. With the requirement for regenerative operation, the DC and AC Systems controllers are quite similar in design complexity and number of components. The Current Source/Slip Regulated AC Drive System is concluded to be superior for winch service since it best satisfies the critical regeneration and overload requirements, and uses the most rugged and reliable drive motor.

ADMINISTRATIVE INFORMATION

This work was accomplished under Task Area 15625, Project SSL51, Program Element 63705N, and Work Unit 1-1175-138.

INTRODUCTION

The Naval Sea Systems Command is conducting a research and development program for Underway Replenishment of Surface Ships (SSL51). This program provides for the continuing advanced development of the specialized equipment required to replenish surface ships at sea with fuel, ammunition, food and supplies which are vital to maintaining a credible Naval force. The equipment developed will provide standardized components which are inherently more reliable, maintainable and resistant to the rigors of the sea environment.

In support of this program, the David W. Taylor Naval Ship Research and Development Center has been tasked to develop a Standard Electric

Winch Drive which can be competitively procured. The first phase of this task is to conduct a cost and feasibility study of all commercially available electric winch drives; specifically all types of solid state (silicon controlled rectifier) AC and DC drives.

This report investigates the cost and feasibility of all-electric winch drives for underway replenishment (UNREP) highline/spanwire winches, particularly those drives using Silicon Controlled Rectifier (SCR) solid-state motor controls. Service requirements including performance parameters and reliability and maintainability requirements are identified. Basic winch system performance requirements are presented; and each component block of the basic winch system functional block diagram is identified and discussed. Candidate all-electric drive DC Controller systems and AC Controller systems are treated in detail including functional system description, availability of motor/controller, design features, description of hardware and specifications, reliability and maintainability considerations, built-in test features, and motor/controller interchangeability. (Note: It is customary in the motor-control field to label a controller by the type of motor in the system; that is, a DC Controller controls a DC Motor and an AC Controller controls an AC Motor. Both controllers are powered by 3-phase, 60-Hz primary power.) Another section of this report presents system performance predictions based upon the conclusions reached in this study, and summarizes the characteristics of four major DC and AC All-Electric drive contenders for winch service. Costing considerations are broken out as: typical motor pricing, typical controller pricing, typical isolation transformer pricing, installation cost considerations, and support considerations. As the result of assessing the findings in this report, recommendations for future developmental actions are given.

BACKGROUND

Since the mid-1950's the Navy has been using electrohydraulic transmissions for most variable speed applications, especially winches. These

transmissions have been expensive and difficult to buy and maintain. With the advent of the Silicon Controlled Rectifier (SCR), trade named "Thyristor," in 1955 and the subsequent development of commercial solid state motor controls, interest began to build in the potential use of all-electric drives for powering shipboard winches.

Prior Navy effort in this area has resulted in the development of an experimental DC variable speed 30-hp (30.4-hp metric) winch drive for a refueling-at-sea saddle winch. The experimental winch was subjected to testing in land-based test facilities and has been evaluated aboard the USS WABASH (AOR-5) in 1976. Satisfactory operation of this variable speed electric drive has encouraged the further application of electric winch drives.

This successful application of the 30-hp (30.4-hp metric), DC drive has initially verified the feasibility and reliability of solid state electric drives. The intent of this study was to select an optimum, solid state, electric drive to power a highline/spanwire UNREP winch--this specific winch having the most severe UNREP operational requirements. To select a specific type of electric drive for the highline/spanwire winch all types (both AC and DC) of commercially available, solid state, electric drives were considered. In the final selection of the candidate prototype drive system to be breadboarded for this application, the main factors in the decision were: (1) bidirectional operation of the drive unit together with winch generated power feedback (power regeneration) into the ship's basic power system--in essence these two features define "Four Quadrant Operation" in the speed-torque plane, (2) maintainability--elimination of all possible periodic maintenance requirements especially brush replacement in DC motors, which also generate electromagnetic interference (EMI) problems for electronic equipment, and (3) reliability--in this area it is shown that the intrinsic component reliability of thyristors is sufficiently high to justify their use in this application, their circuit application is identical for both AC and DC drives, and finally the commercial justification of DC drives reliability based on extensive, industry-wide, use of these drives.

Cost was NOT considered as a selection criterion for the type of drive, but was considered to provide a comparative tool for evaluating an all-electric drive system with respect to the electrohydraulic drive system currently being procured for this highline/spanwire winch.

SERVICE REQUIREMENTS

Underway replenishment winch drives must be suitable for shipboard installation and maintenance by naval personnel. With minor modifications, particularly in enclosure design and provision for heat dissipation, industrial electric drives were evaluated for feasibility of the basic electric system for shipboard winches.

Some additional modifications of the industrial equipment will be required to adapt the industrial equipment to the naval shipboard environment; such modifications may include more stringent EMI shielding and filtering and additional cooling.

Performance Parameters

General guidance for the performance of shipboard electric winch drives is given in the following documents, although they are not at this time considered firm requirements for acquisition of prototype, industrial, electric drives:

MIL-W-15808	Electric Winch
MIL-STD-1399	(Section 103 - Ship's AC Power)
MIL-W-17265E	Winch, General
MIL-W-17265/1A	Winch, Specific

The basic highline/spanwire winch system block diagram is shown in Figure 1. The performance functions per NAVSEC requirements of the individual blocks in the system are:

Command Input: Generates, variable magnitude, bidirectional speed signals via a manual control lever and transmits these to the controller. The standard Navy Command Input control shall be used with only minor modifications to accommodate the all-electric winch drive control requirements.

Controller: Operates from ship's 440-V, 3-phase, 60-Hz power; provides power to winch drive motor as directed by command input signal. Controller will not be exposed directly to the weather.

Motor: Watertight motors must operate aboard ship in a severe ocean environment. The highline/spanwire application requires a 200-hp (202.8-hp metric) motor. For AC motor drives, a NEMA B induction motor must be employed. For DC motor drives, a DC shunt-wound motor must be selected.

Gearing: The gearing shall be part of the standard Navy winch bed. Gear ratios shall be adjusted to match motor and winch-drum speeds for optimum system performance.

Winch Drum: The winch-drum mechanical assembly shall be part of the Navy standard winch bed.

Ram Tensioner: The ram tensioner is a standard Navy device used to automatically adjust the length of the highline/spanwire cable to compensate for ship motion induced cable length changes.

Overall System Performance Parameters:

Rated Full Load - 20,000 lb (9072 kg) line tension, Speed 240 ft/min (1.219 m/s).

Maximum Overload - 30,000 lb (13,608 kg) line tension, Speed 120 ft/min (0.609 m/s).

Rated Line Speed for Haul-in or Pay-out - 240 ft/min (1.219 m/s).

Minimum Line Cable Speed for Haul-in or Pay-out - 24 ft/min (0.12 m/s).

Average Layer Diameter of Cable On Winch Drum - 35.7 in. (0.907 m).

Rated Winch Drum Speed - 24.4 rpm.

Bidirectional Winch Operation - Required.

Regenerative Controller Operation - Required.

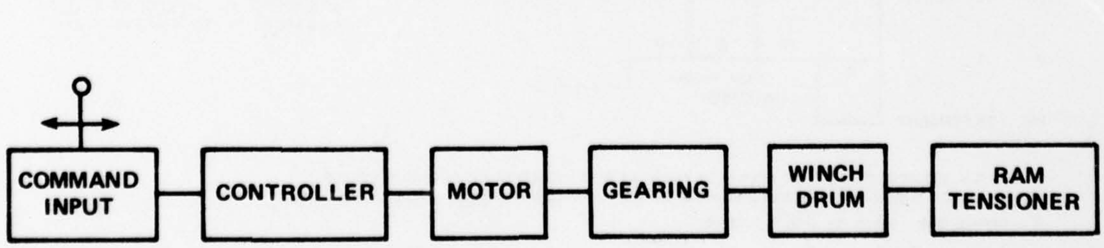
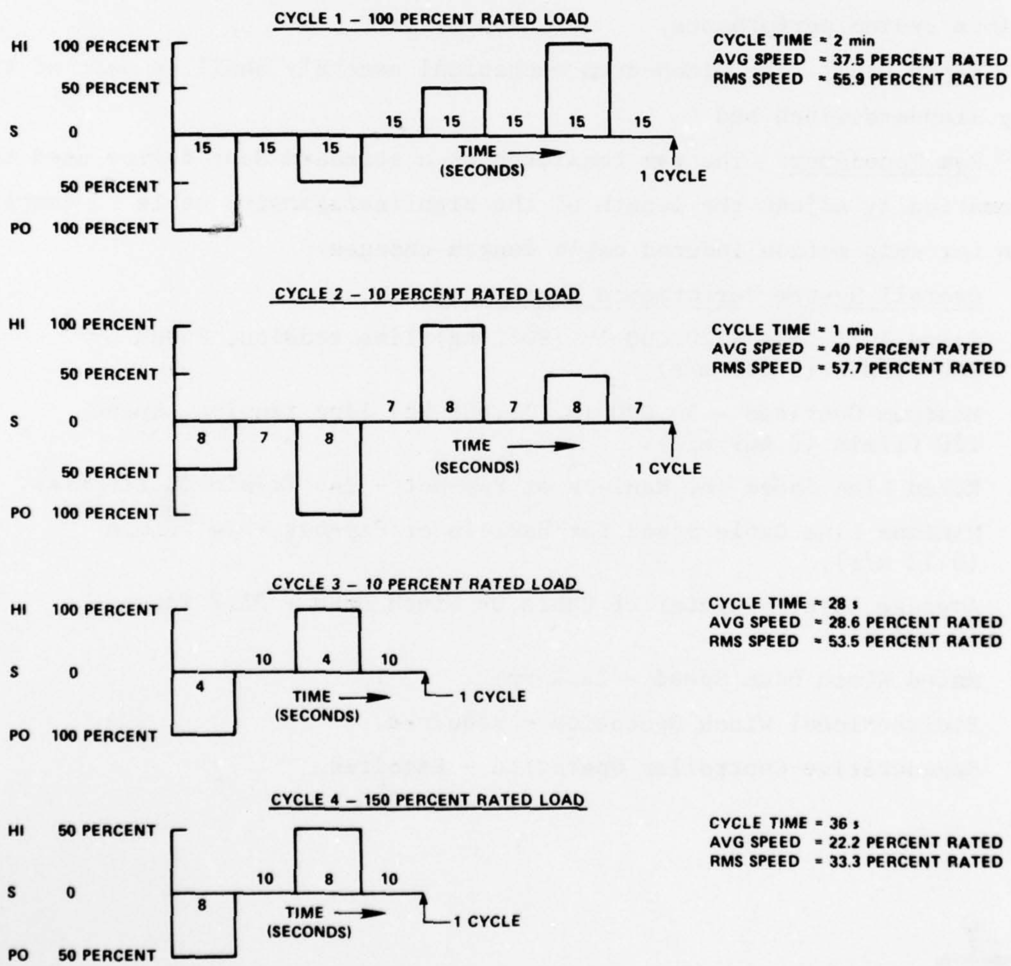


Figure 1 - Winch System Block Diagram

Operational Evaluation Program (Test)

The specific UNREP operational evaluation program that has been established for the highline/spanwire winch is given in Figure 2. This program represents the operational, "worst case" mission profile to which a highline/spanwire winch would be subjected in any UNREP mission. This program was developed jointly by cognizant personnel from Naval Ship Weapons System Engineering Station (NSWSES) and Naval Ship Engineering Center (NAVSEC).



CYCLE 5 – 100 PERCENT RATED SPEED, PAYOUT AT 9/10 RATED LOAD FOR 60 SECONDS
TOTAL TEST: (1-25/2-10/1-25/2-10/1-25/2-10/3-10/4-1/5-1); (CYCLE NUMBER – REPEAT XX TIMES)
S – SPEED; (HI) – HAUL-IN; (PO) – PAY-OUT

Figure 2 - Operational Profiles for the Highline/Spanwire Winch

Off-the-Shelf Industrial Items

Variable speed electric drives developed for industrial and commercial marine applications are currently operating with reliable performance in the severe environmental conditions of textile mill, steel mills, offshore drilling rigs, and aboard Great Lakes ships. Since the service requirements for naval applications are generally not much more demanding, off-the-shelf industrial components will be satisfactory for naval service provided the appropriate housing exists to handle the additional waterproofing, heat dissipation, and vibration.

Multiple Sourcing

One of the major service requirements is to acquire Navy-approved designs for electric winch drives that are fully described in Navy drawings and specifications and can be acquired competitively for installations as needed. Multiple sources for these systems are desired; but the design details of the all-electric winch systems from the various sources need not be identical.

Motor/Controller Interchangeability. In the near term, it is acceptable to consider the motor and controller to be matched to each other when a system is installed. One of the longer range service objectives is to generate motor/controller interface specifications such that interchangeability of motor and controller units would be possible. The complexity of the thyristor circuitry of the controller currently precludes establishing general output specifications for the controller; however, the electrical parameters of the motors (both AC and DC) do allow a controller to be matched to any motor, if the critical electrical parameters of the motor are specified by the manufacturer.

Reliability and Maintainability Requirements

The all-electric drive has a number of inherent attributes that promote winch system reliability and maintainability as well as effectiveness.

Sufficient design margin must be built into the winch system, however, to avoid overstressing the motor through drawing excessively high currents during speed reversals and sudden braking.

System Availability. Because winch reliability and maintainability are crucial to the success of underway replenishment (UNREP) missions, the availability of the winch must be maximized. In Military Standardization Handbook MIL-HDBK-217B, entitled Reliability Prediction of Electronic Equipment, System Availability (A) is expressed as:

$$A = 1/(1+MTTR/MTBF)$$

where MTBF = mean time between failures and MTTR = mean time to repair

The System Availability (A) design goal for most electrical and electronic systems has been established as greater than or equal to 0.95 and this is readily achieved by making MTBF $\geq$ 20 MTTR. It follows from the above equation that availability can be maximized through making the MTTR as short a time interval as possible and lengthening the MTBF through choice of design approach, selection of parts with low failure rates, stressing parts well below their maximum ratings, providing built-in test features that minimize the time required to isolate a faulty component, and construction that facilitates quick part or module replacement.

A MTBF of 1500 hr is a desirable goal for an underway replenishment all-electric winch drive. This time is consistent with an average of about 1000 hr of equipment operation that is experienced between normal ship overhaul periods.

With a MTBF of 1500 hr and an availability of 0.95 the resultant MTTR must be less than 75 hr. Based on industry's experience with the solid state DC drives, this MTTR is easily met and even with the complexity of the thyristor circuitry a worst case of 6 hr for MTTR is the accepted figure.

Ease of Maintenance. To ensure rapid, convenient maintenance and servicing, the thyristor converter unit (that converts AC-type power into variable voltage DC-type power for operation of DC motors or into variable current for reconstruction into variable-frequency, 3-phase AC power for operation of AC motors) must be completely repairable via access from the front panel only. Thyristor converter units should be constructed using plug-in control modules so that maintenance and repair may be facilitated through module replacement. Printed circuit board replacement must also be accomplished without upsetting any of the adjustable parameters. Adjustable components such as potentiometers should be minimized and should have a numbered scale with an arrow to permit resetting the adjustment to its proper value. Adjustments of any one parameter; such as, acceleration, minimum and maximum speed, current limit, stability setting should not affect the adjustment of any other parameter.

SCR transient voltage and current protection snubber circuits should be packaged in readily replaceable modules.

Built-In Test Features, Indicators, and Alarms. Each thyristor converter unit should contain a built-in monitoring system to monitor key parameters for checkout and troubleshooting. The monitoring system should consist of meters and indicating lights and should be capable of being switched from one parameter to another for checking out the converter. The key parameters should include converter AC voltage, all the DC power supply voltages, armature voltage and current and field voltage (for the DC motor), DC-to-AC inverter output voltage (for the AC motor), and any other parameter that is deemed necessary to facilitate maintenance and troubleshooting. Test jacks should be provided as part of the monitoring system.

EMI and Line-Notching Considerations

Any electrical disturbance that causes an undesirable response or a malfunction in equipment is called Electromagnetic Interference (EMI). It

manifests itself in a radio communications receiver as noise. The frequency spectrum of this disturbance may be distributed anywhere in the entire range from low audio frequencies to super-high frequencies (3 GHz to 30 GHz) and above. Interference signals usually originate from one or more particular components or devices, rather than from the entire system. All components and devices, such as diodes and transistors, that are nonlinear (that is, current and voltage waveshapes are not identical) produce harmonics at frequencies that are multiples of the fundamental frequency.

Silicon-Controlled Rectifier (SCR) diodes exhibit a stored-charge phenomenon that is characteristic of all diodes: there is a certain amount of conduction in the opposite direction just after the AC waveform goes from the forward conducting phase to the reverse (normally considered to be non-conducting) phase. Conduction in the diode continues until all stored charges are swept out. Not only is the duration of this effect critical, but the actual shape of the current pulse at the end of the reverse conduction period determines the amount and spectral distribution of the harmonics generated. In fact, diodes called "Step-Recovery Diodes" possessing very steep fly-back current characteristics are used for highly efficient harmonic generation at microwave frequencies. Conversely, "Hot-Carrier Diodes" with very small stored charge characteristics (less than two picocoulombs) are used as radio frequency detectors, where reverse conduction cannot be tolerated.

Another source of undesirable harmonics, often called "brush noise," is caused by arcing between brushes and commutators in DC electric motors. The rapid initiation and quenching of the arc discharge result in electrical impulses with very high harmonic content.

"Line Notching" describes the effect where the primary AC input to a SCR-controlled drive is effectively short-circuited for four to five microsecond periods due to the turn-on and turn-off characteristics of the SCR diodes. This form of interference is especially insidious since it is imposed directly on the AC primary power source through the "crow-bar" shorting effect, rather than indirectly by radiation or by conduction.

Low data-rate communications systems such as analog voice circuits have relatively high tolerance to broadband EMI-caused noise, because (1) they are narrow bandwidth systems, and (2) there is considerable redundancy in speech. On the other hand, information transmitted at the high data rates that characterize current digital radio communication circuits, especially with those circuits employing earth satellites as radio relay links, is very vulnerable to interruption by noise bursts of relatively short duration.

The skill and technical sophistication of the SCR Controller designer determines to a large extent the level of harmonic content and other spurious output from the SCR Drive circuits. Replenishment at Sea imposes the additional requirement that the SCR Drive must be compatible with other equipment aboard, particularly radios and radars. Since industrial SCR Controller applications rarely require working in the proximity of sensitive electromagnetic sensors, such as found aboard U.S. Navy ships, the level of EMI-attenuation suitable for industrial service is not expected to be acceptable. Accordingly, additional effort will be required for military electromagnetic environments. Engineering practice dictates analyzing and evaluating the degree of EMI suppression of a particular SCR drive design; measuring and determining the harmonic and spurious noise content of the actual production hardware; and attenuating noise output through additional interference-minimizing techniques as required before the drive is released for service in the Fleet.

BASIC WINCH SYSTEM

The Basic Winch System Function Block Diagram is shown in Figure 3 for either a Highline or Spanwire Winch System. The function of each component block is discussed below:

Ship's Power - the definitions and constraints associated with the use of Ship's Power are specified in MIL-STD-1399 (NAVY)/Section 103.

Isolation Transformer - an isolation transformer at the power input of each thyristor converter unit is needed (1) to match the available

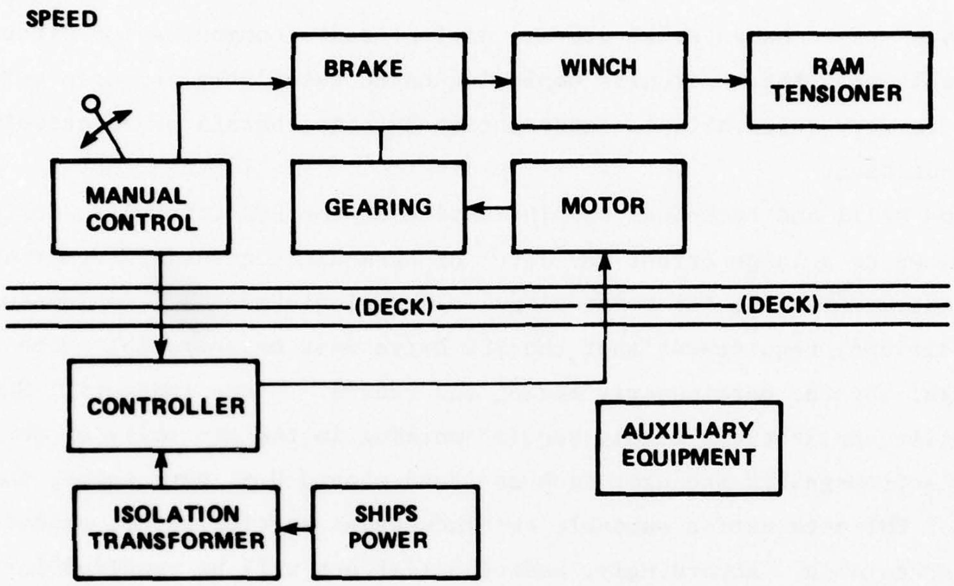


Figure 3 - Basic Winch System Functional Block Diagram

ship's service voltage to the voltage required by the thyristor converter unit, (2) to provide the proper impedance to reduce the effects of line notching, and (3) to provide the correct number of windings in the transformer secondary to interface with the thyristor converter unit. The transformer primary windings shall be delta-connected; and the secondary windings shall be connected as required to provide the proper interface between equipments.

Manual control - manual speed commands from the winch operator are accepted via a manual control lever which converts these speed requirements into proportional electrical signals that are routed to the controller.

Controller - the Controller is the major solid state (thyristor) control unit. It accepts AC primary power from the isolation transformer and electrical control signals from winch manual control and produces the appropriate AC or DC electrical output to drive the winch motor.

Motor - the basic winch drive motor is mounted on a standard NAVY winch bed together with the winch drum and associated manual winch brakes, gearing, etc. The motor (AC or DC) accepts controlled power output from the controller and provides proportional output shaft speed to the winch drum via the winch gearing. Calculated power requirements are 150 hp (152.1-hp metric). Therefore, to provide some margin, candidate motors for this specific winch application are:

AC: 200-hp (202.8-hp metric), 450-VAC, 3-phase, 60-Hz, NEMA B Induction Motor

DC: 200-hp (202.8-hp metric), 500-VDC Armature and 240-VDC Field Shunt-Wound Motor

Winch - the winch consists of the drum, gearing, manual brakes, etc., that manipulate the wire rope of the winch system. The winch drum and associated equipment are currently being standardized and packaged in a compact unit to be designated as a standard Navy winch.

Ram Tensioner - the Ram Tensioner is an air/hydraulic ram and cylinder unit which operates semi-independently of the winch drive to hold the wire rope under constant tension. Electrical signals from limit switches on the ram-tensioner unit are fed back to the manual control unit to automatically control the winch to keep the ram tensioner within its normal operating range.

Auxiliary Equipment - the Auxiliary Equipment consists of the essential electrical/mechanical interconnecting equipment and specialized temperature sensing equipment that are necessary to ensure reliability of controller/motor operation. The specialized motor/controller equipment for a developmental system includes:

Thermocouples (Internal and Ambient)

Temperature Recorder (Automatic with alarm outputs)

Heaters, fans, air conditioning (requirements not firm at this time)

Over-temperature (audio/visual) indicators and alarms

Gearing - the winch gearing matches the motor speed/torque output to the cable-tension/speed requirements of the winch drum.

Brake - the semi-automatic brake allows the motor to be electrically de-energized during all "zero-speed" command conditions regardless of the condition of the load (tension) on the winch (cable). This "floating" of the motor during "zero-speed" command periods allows the motor to cool off during these "off" periods and thus permits the selection of the minimum hp-sized motor for a given application. This braking package will interface with the motor/controller in the manual control and will normally be operated (brake applied) within some "dead band" region surrounding the "zero-speed" command position of the manual-speed control lever. The brake will be electro-mechanically actuated.

WINCH SYSTEM PERFORMANCE REQUIREMENTS

The two load conditions that the winch drive must be able to handle are:

1. Rated full load - 20,000 lb (9072 kg) at a line speed of 240 ft/min (1.219 m/s).

2. Maximum overload - 30,000 lb (13,608 kg) at a line speed of 120 ft/min (0.609 m/s).

The current performance parameters of the winch system are summarized in the Winch Duty Cycle Profile shown in Figure 2. The total testing cycle evaluation procedure is defined by the line entitled "Total Test" in the figure. It is important to note that zero rise times are shown on the diagrams and the system rise times are not specified. Lack of this data is an admitted deficiency in the current operational knowledge of the required winch system performance, but the theoretical system rise times are amenable to analysis and calculation.

CANDIDATE DC DRIVE SYSTEM

All of the candidate industrial DC drive systems are of one basic design: the applied armature voltage of a shunt DC motor is controlled to effect speed control at a constant torque up to the rated motor speed. Over-rated speed can only be obtained through torque reduction; that is, constant horsepower operation via field weakening of the separately-excited shunt field.

DC drive systems make up the majority of the solid-state drives currently used in industry. The major system drawbacks from the naval application viewpoint are basically related to the DC drive motor with its higher cost, mandatory brush/commutator maintenance problems and higher rotor inertia. The DC system is somewhat more complicated than most AC systems, since the DC system requires two SCR converters to provide bidirectional motor operation and power regeneration that feeds electric power back directly into the primary power system.

FUNCTIONAL SYSTEM DESCRIPTION

The key components of the Candidate DC Drive System are the DC Controller and the DC Motor. Since the other remaining components are practically identical for both the DC and the AC all-electric winch drive systems, only the controllers and motors shall be discussed in detail. The controller is designed to control the DC Motor over a wide and infinitely adjustable speed range from zero to the rated motor speed.

The Block Diagram of the DC Controller is shown in Figure 4. The controller consists of the following sections:

Rectifier Bridge - the rectifier bridge consists of two separate 3-phase, full-wave, 6-pulse bridges with each bridge consisting of 6-silicon controller rectifier (SCR) diodes mounted on heat sinks. The two bridges are connected in an inverse parallel configuration, and this rectifier bridge section may be designed to operate from either a 230-V or a 460-V, 3-phase, 60-Hz AC primary power source. The rectifier bridge performs two major functions as the armature supply:

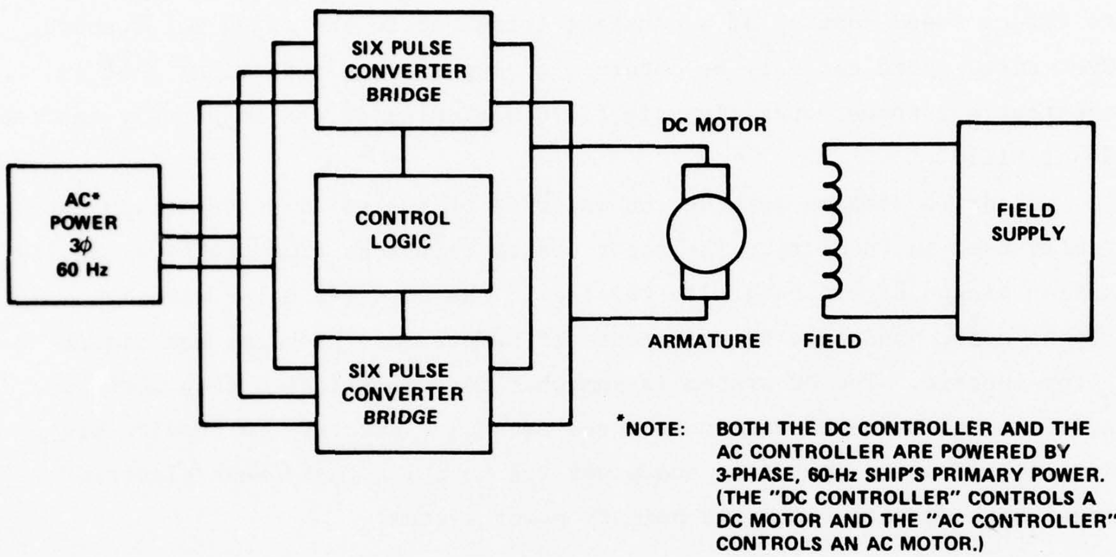


Figure 4 - DC Controller Block Diagram

1. Ship's service AC voltage is converted to DC voltage by rectification of the 3-phase input AC waveform.

2. The amplitude of the DC armature voltage is varied by controlling the size of the portion of the rectified 3-phase AC waveform which is passed on to the armature.

When the DC motor is being overhauled during the pay-out phase of the operation, the motor acts as a generator when the counter EMF is greater than the output voltage. The second rectifier with reversed diodes then transfers the power generated to the primary AC line. (The functions of the two bridges are reversed for motor rotation in the opposite direction.)

Control Logic - the logic circuits prevent the SCR's in one rectifier bridge from being fired while current is still flowing in the other rectifier bridge. This is accomplished by two Firing Logic Pulse Amplifier circuits: one for forward bridge conduction and the other for reverse bridge conduction. The logic also protects against malfunctions including improper phase sequence, loss of phase, and overcurrent.

Field Supply - the DC motor shunt field is separately excited from a constant-voltage DC power source that is obtained by half-wave rectification of the 3-phase line voltage. A 230-VAC line provides a 150-VDC motor shunt field supply; and a 460-VAC line provides a 300-VDC supply.

DC DRIVE MOTOR/CONTROLLER AVAILABILITY

The DC SCR Controller is available as a standard industrial product for this application. Accordingly, the manufacturers recommend that the following limitations be observed and obviated:

1. Since a NEMA 1 Cabinet is the standard enclosure supplied with the controller, the unit must be operated in a sheltered environment and not exposed to rain, extreme temperatures, salt spray or any other adverse weather conditions.

2. Shipboard operation of the controller is not recommended without additional provisions for isolation-mounting the unit to withstand the expected shipboard vibration environment.

3. Because the controller is designed to operate from commercial primary power, no harmonic filtering or line-notching suppression is provided. Accordingly, operation of this unit on the ship's 60-Hz power supply would result in abnormal operation of other electrical systems aboard ship on the same primary supply. Therefore, additional effort to reduce interaction with the primary power supply to a tolerable level will be required.

The two-hundred horsepower DC motor for this application requires a watertight enclosure. Although this is not a standard industrial product, it is within the state of the art, and may be built to special order.

Design Features

Typical features offered by the DC Controller manufacturers include:

1. Armature Voltage/Tachometer Feedback for Speed Regulation and Drift Control
2. Independently Adjustable Linear Acceleration and Deceleration Control
3. Separately Adjustable Jog Speed
4. Maximum Speed Adjustment
5. IR Compensation Circuitry (for Armature Feedback Applications)
6. Instantaneous Fault Trip Circuitry
7. Adjustable Current Limit Control
8. Field Loss Protection
9. Pulse-Train SCR Firing Circuitry
10. Integrated Circuit Amplifier Circuitry
11. Modular Construction
12. Test/Meter Drive Monitor

Protective features as follows:

1. AC Line Reactors and Transient Suppressors
2. DV/DT Protection
3. Instantaneous (5 ms) fault trip circuitry
4. Single Phase Protection
5. DC Motor Contactor with Undervoltage Protection
6. Adequate Fusing for Jam Protection (AC Lines and Armature)

DC Drive Hardware Description (Specification)

A typical DC SCR Controller can meet the following specifications:

Horsepower Rating - 200 hp (202.8-hp metric)
Speed Range - 10 to 100 percent of rated rpm
Overload Capacity - 150 percent overload for one minute
Motor Speed Regulation - 5 percent of base speed
AC Power Supply - 480-VAC, 3-phase, 50/60-Hz

Standard Adjustments - Minimum - Maximum Speed Adjustment

Current Limit Setting
IR Compensation
Crossover Frequency Adjustment

Ambient Temperature - +10 C to +40 C

Enclosure Type - NEMA 1

DC Controller Weight - 265 lb (120.2 kg)

DC Motor Weight - 5,500 lb (2495 kg)

A typical Input Isolation Transformer can meet the following specifications:

Volt-Ampere Rating - 300 KVA

Number of Phase - 3 phases

Primary Voltage - 460 VAC

Frequency - 60 Hz

Secondary Voltage - 460 VAC

Secondary Configuration - WYE-Connected

Enclosure Type - NEMA 1

Transformer Weight - 1200 lb (544 kg)

DC Drive Reliability and Maintainability Considerations

Although industrial SCR Drives are not ordinarily built to meet MIL-Specifications, they are designed conservatively in order to operate reliably with a minimum of failure over long time periods because:

1. Many applications (such as glass blowing and synthetic textile fibers manufacturing) cannot tolerate complete shutdowns resulting in extensive damage due to material hardening.

2. Skilled electronic technicians are seldom available, leaving servicing and repair to the maintenance crew who may have little experience with SCR Controllers.

Reliability data on industrial products are seldom directly available from the manufacturer; however, the component part stress levels of SCR Drive design to good industrial practice are known. They are between 60 percent and 80 percent of their rated capacities. Accordingly, a reliability prediction can be made from available component parts data. The

reliability prediction made in paragraph entitled MTBF Prediction of this report (page 69, APPENDIX D) is based upon the MIL-HDBK-217B, Parts Stress Analysis approach, using schematics and diagrams in the instruction manual for a standard industrial 150-hp SCR Controller. The total Controller parts failure rate of 180.501 failures per million hours, or a Mean-Time-Between-Failure (MTBF) or 5540 hr, can be greatly improved by employing the next higher quality level of transistors and SCR thyristor diodes resulting in an 80-percent part failure rate reduction for these parts:

(18 each)	PNP Transistor	(0.8)	55.080 =	44.064	failures/10^6 hr
(21 each)	NPN Transistor	(0.8)	37.800 =	30.240	
(1 each)	FET Transistor	(0.8)	4.350 =	3.480	
(12 each)	SCR Thyristor	(0.8)	45.756 =	36.604	
	REDUCTION			114.388	failures/10^6 hr

The total part failure rate for the upgraded DC SCR Controller design is therefore: 180.501 less 114.388, or 66.113 failures per million hours, or the MTBF of the DC SCR Controller is 15.125 hr. The prediction can be further improved by upgrading the quality of the remaining component parts.

The above exercise demonstrates that a considerable reduction in failure rates results when commercial-grade transistors and SCR's are upgraded to their next higher quality level. Accordingly, the reliability of the controller can be enhanced by a nominal increase in the cost of the solid-state components.

Maintainability features of the industrial DC SCR Controller include:

1. Power Line Fuses

2. Thermal Protection through a temperature sensor on the SCR Power Bridge which provides safe shutdown due to overheating

3. Motor Armature Loop Contactor capable of breaking full-load current

4. Instantaneous Static Trip Protection provides safe shutdown when currents exceed 300-percent rated values

5. Current Limit Protection sets the maximum steady-state current the drive will supply to provide current control regardless of motor speed

6. Motor Inverse Time Overload Protection guards against sustained over-current conditions for long time periods

7. Short Circuit Protection is provided through fast acting semi-conductor fuses

8. Line Transient Protection provided by voltage transient (DV/DT) suppression circuitry and current transient (DI/DT) chokes to limit rate of current rise

9. Single Phase Protection prevents damage in the event of any phase loss

10. Phase Sequence Protection prevents drive operation with incorrect phase sequence

11. Under-Voltage Protection through a run-lockout feature which requires all power supplies to be energized before the drive will operate

12. Quick replacement of Printed Circuit Boards

Built-In Test Features

Built-in test features include the following:

1. Test Meter with Sequencing Switch

2. Easy access to Main Rectifier Bridges and Printed Circuit Boards

3. Detailed Troubleshooting Table for identifying probable cause of six system faults

4. Troubleshooting Logic Blocks Flow Chart (Fault Logic Diagrams) for each of the six system faults:

a. Motor does not run

b. Motor runs at reduced speed only

c. Motor runs at full speed only

d. Blows fuses or activates instantaneous static trips (IST) on startup

e. Motor runs in one direction only or does not regenerate

f. IST's or blows fuses when reversing operation or regenerating

DC Motor/Controller Interchangeability

Initially, manufacturers recommend that the DC motor and DC SCR Controller be supplied as a matched system; for the armature reactance of the motor determines mainly what inductance compensation must be provided to filter the rectified, pulsating current from the converter. The manufacturer can eventually supply a DC Controller that could be matched to DC motors other than the one he has selected, provided the motor manufacturer can provide the controller designer with armature reactance values plus inter-pole and main field pole magnetic design data of the specified motor. Currently, the inter-pole and main field pole magnetic design of any particular DC motor makes the DC motor/controller interchangeability problem too complex a problem to analyze and/or resolve at this stage of the electric drive development.

CANDIDATE AC DRIVE SYSTEM

The candidate AC drive systems can be classified according to inverter type: variable voltage, pulsewidth modulator, and current source inverters.

Variable Voltage Inverter - the variable voltage inverter system generates a constant "volts-per-hertz" drive signal which is applied directly to the induction motor to control its output speed. A feedback loop senses the actual motor speed and causes the control circuitry to adjust the motor's input until the proper output speed is obtained. These systems have relatively slow dynamic response, require complex thyristor firing control, have no simple regenerative capabilities, and are speed-range limited in terms of the upper speed limit due to the required regeneration of elevated applied voltages at high speeds to maintain the "volts-per-hertz" criteria of their basic operation. Regenerative motor operation causes polarity reversals of their basic DC bus and requires additional complex sensing and switching control circuitry to provide any possible regeneration scheme.

Pulsewidth Modulator Inverter - the pulsewidth modulator (PWM) inverter system provides a common DC bus voltage from which the inverter generates

(by a sampling technique) a variable-frequency AC voltage (whose waveshape approximates a sinewave) to drive the motor. The PWM inverter is effectively an "open loop," feed forward system in that it provides the signal to which the induction motor must respond independently of the load conditions. Regenerative electric power from the motor's load (such as an overhauling winch) is fed back into the DC bus; and only if other loads are on the same DC bus can the PWM system dissipate this regenerative power. The PWM system requires complex logic circuitry for the generation of its output motor frequency, has no simple regenerative power features to allow power to be fed back directly into the power system, and the system does not respond to any dynamic load conditions, thus allowing the motor to be subject to all overload conditions.

Current Source Inverter - the current source inverter type of drive system controls the current supplied to the motor and has an automatic speed sensing feedback loop that controls the magnitude of the motor's input current. The system compares the inverter output frequency with the output shaft speed of the motor. The difference between them is the "slip" of the induction motor, by definition. The "slip" signal is then used to regulate the total current supplied to the motor. This "slip regulation" allows the system to automatically respond to dynamic load conditions in such a manner that maximum motor torque is delivered to the load throughout the total speed range of the drive system. In addition to providing bidirectional drive signals to the motor, the system automatically provides for regenerative power to be fed back directly into the power system. The effective motor protection provided by this slip regulation together with the ease of pumping regenerative power directly back into the power system make the current source/slip regulated AC drive system the choice as a candidate for the all-electric winch drive application. A possible drawback to the current-source/slip-regulated system is the need for a tachometer. The problems usually associated with mechanical tachometers may be averted by employing recently-developed, highly-reliable optical tachometers.

FUNCTIONAL SYSTEM DESCRIPTION

The key components of the Candidate AC Drive System are the AC Controller and the AC Motor. Since the remaining components of the winch system are standard items or an item such as the gearing that is relatively easy to alter, only the controller and the motor shall be discussed in detail.

The purpose and function of the controller and motor are to provide rotational energy to drive the winch drum through the gearing. The controller produces rapid and stable positive and negative torque responses in the AC Motor at speeds that vary from zero to the rated speed. The AC Drive System is fully regenerative and is capable of four-quadrant operation; that is, the controller can transfer power both from the motor to the load and conversely from the motor back into the primary AC power line and can cause motor rotation in both the forward and reverse directions.

The Block Diagram of the AC Controller is shown in Figure 5. The AC Controller consists of the CONVERTER RECTIFIER section, the INVERTER section, and the CONTROL LOGIC section. The silicon controlled-rectifier CONVERTER RECTIFIER converts the 3-phase AC input power into variable DC current which is smoothed by a CURRENT LINK FILTER, shown as an inductor for the constant current source.

The CONTROL LOGIC rectifier acts so as to control the current through the CURRENT LINK FILTER. The INVERTER sequentially switches the DC LINK current so as to generate 3-phase AC current for the motor. The CONTROL LOGIC provides proper phase rotation and alternating current frequency to the motor to satisfy the load requirements. Input speed signal commands and feedback signals from the TACHOMETER determine how the CONTROL LOGIC controls the firing of the thyristors in both the CONVERTER RECTIFIER and the INVERTER. The primary function of the CONTROL LOGIC is to control the DC current from the CONVERTER RECTIFIER and the output frequency of the INVERTER (so as to control the motor current, torque, and speed).

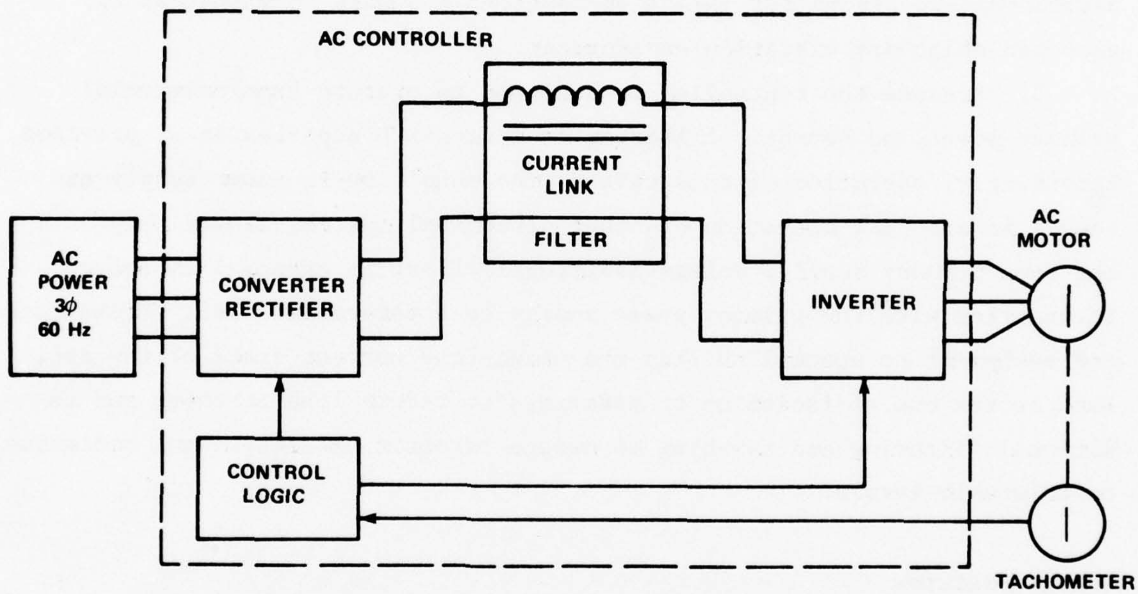


Figure 5 - AC Controller Block Diagram

AC DRIVE MOTOR/CONTROLLER AVAILABILITY

Both the 200-hp AC Motor and SCR Controller are available as standard industrial products. Accordingly, the manufacturer recommends that the following limitations be observed and obviated:

1. Since a NEMA 1 Cabinet is the standard enclosure supplied with the controller, the unit must be operated in a sheltered environment and not exposed to rain, extreme temperature, salt spray or any other adverse weather condition.

2. Shipboard operation of the controller is not recommended without additional provisions for isolation-mounting the unit to withstand the expected shipboard vibration environment.

3. Because the controller is designed to operate from commercial primary power, no harmonic filtering or line-notch suppression is provided. Accordingly, operation of this unit on the ship's 60-Hz power supply may result in abnormal operation of other electrical systems aboard ship on the same primary supply, unless additional effort is expended to reduce interaction with the primary power supply to a tolerable level. Techniques and equipment to accomplish this are within the current state of the art, such as the use of isolation transformers to reduce line notching and additional filtering and snubbing to reduce harmonic conduction and radiation to tolerable levels.

Design Features

Typical features offered by the AC Controller manufacturers include:

1. Analog DC Tachometer or Digital Tachometer Feedback options
2. Minimum Motor-Current control
3. Current and Torque limiting for controlling maximum control level of rated slip and current. (This keeps the motor from experiencing NEMA locked-rotor conditions.)
4. Output Over-Voltage Trip
5. Speed Regulation
6. Maximum Speed Adjustment
7. Oscillator Offset that allows motor to remain stopped
8. Tachometer Compensation which corrects for component tolerances in Tachometer loop

9. Frequency Response Compensation that adjusts the response time of the speed regulator

10. Reverse Trim control that corrects for component tolerances in the tachometer loop in the reverse mode

11. Reverse Balance correction for negative speed error voltages

12. Rate Feedback setting for dampening speed loop to eliminate rpm overshoots

13. Slip Compensation for adjusting the various slip requirements of different motors

Protective features of the AC Controller include:

1. SCR fuses
2. Input Voltage Phase-Sequence Protection
3. Transient Suppression Networks
4. Control Fuses
5. Overload Protection
6. Over-Voltage Trip
7. High Ambient Cabinet Temperature and Heatsink Temperature Protection

AC Drive Hardware Description (Specification)

A typical AC SCR Controller can meet the following specifications:

Horsepower rating - 200 hp (202.8-hp metric)

Input Voltage - 460-VAC, 3-phase, 60-Hz

Steady-State Speed Regulation - 1 percent of top speed for 95-percent load change

Ambient Temperature - +10 C to +40 C

Cooling - Forced air, blowers and/or fans

Enclosure Type - NEMA 1

AC Controller Weight - 3000 lb (1361 kg)

AC Motor Weight - 2000 lb (907 kg)

A typical Input Isolation Transformer can meet the following specifications:

Volt-Ampere Rating - 300 KVA

Number of Phases - 3 Phases

Primary Voltage - 460 VAC

Frequency - 60 Hz

Secondary Voltage - 460 VAC

Secondary Configuration - WYE-Connected

Enclosure Type - NEMA 1

Transformer Weight - 1200 lb (544 kg)

AC Drive Reliability and Maintainability Considerations

Industrial AC SCR Drives are also designed conservatively for trouble-free operation like their DC SCR Drive counterparts. Reliability data are seldom available; particularly because the AC Drive technology is much newer than the DC Drive technology. Fortunately, the Navy has a reliability analysis of AC SCR Drives similar to the proposed winch drive, but of lower horsepower (3 and 30 hp). The predicted MTBF for these overall systems is calculated to be 12,874 hr, which corresponds to a parts failure rate of 77.676 failures per million hours.

The calculated part failure rate of the controller in the militarized system is 31.215 failures per million hours, which corresponds to a MTBF of 32,036 hr. These figures are used in Appendix D of this report in the paragraph entitled MTBF Prediction to construct the reliability prediction of the AC SCR Drive based upon the assumption that increasing the horsepower rating to approximately 200 hp (202.8 hp metric) does not appreciably increase the controller part failure rate provided the individual parts are stressed proportionately the same in both designs.

To determine the operational MTBF of units in the field, the field failure reports of over one-hundred AC SCR Static Power Supplies were analyzed. These units accrued 1,887,000 operating hours over a three-year period. During this time, forty-eight failures were documented and considered as system failures. After analyzing the data, the operational

MTBF of these units was calculated to be 31,900 hr at a 60-percent confidence level. The predicted MTBF for these static power supplies was 8,850 hr. In comparison, the operational MTBF is greater than the predicted MTBF by a factor of 3.6:1.

It would have been informative to compare the militarized DC Controller MTBF and the AC Controller MTBF, especially since the Regenerative AC Drive and the Regenerative DC Drive have identical numbers of SCR's and supporting parts in the main power rectifiers, even though the two systems have different functional tasks. There is a strong likelihood that a definitive analysis based upon actual designs shall result in MTBF's that are almost identical for both the AC and the DC all-electric systems.

Maintainability features of the industrial AC SCR Controller include:

1. Input Voltage Phase Sequence Protection
2. Input Under-Voltage Protection
3. Power-module Thermal Protection
4. Inherent Current Limiting
5. Converter--Output Over-Voltage Trip
6. Three-Phase Motor Overloads Protection
7. Fused Input Rectifier and Control Power Protection
8. DC Link Overload Protection

Built-In Test Features

Built-in test features include the following:

1. Test Meter with Sequencing Switch
2. Easy Access to Main Rectifier Bridges and Printed Circuit Boards
3. Rapid removal and replacement of Printed Circuit Boards
4. Indicator Lamps and Alarms
5. Transient Suppression Networks associated with SCR's, relay coils, and the inverter output circuit
6. High Ambient Cabinet Temperature and Heatsink Temperature Protection
7. Detailed Test and Troubleshooting Procedures including SCR Replacement Instructions

8. Explicit Troubleshooting Guide including Fault Logic Diagrams for:
   a. Drive Does Not Run
   b. Drive Runs Improperly

AC Motor/Controller Interchangeability

Initially, the manufacturers recommend that the AC Motor and AC SCR Controller be supplied as a matched system; for the leakage reactances of the motor determine mainly what capacitance compensation must be provided in the controller to avoid misfiring the silicon-controlled rectifiers. The manufacturers can eventually supply an AC Controller that would mate with any motor provided the motor manufacturer can define the leakage reactance values required of the specified motor. In the near future, it may be entirely practical to design a controller with provision for switching-in a selection of different compensating capacitance values through a tap switch.

SYSTEM PERFORMANCE PREDICTIONS AND SUMMARY

Analytical studies and the witnessing of actual demonstrations of the performance of Static Controller/Motor drives along with the results of the sea trials of the SCR-controlled, all-electric winch drive installed on the USS WABASH (AOR-5) indicate that the all-electric drive is presently feasible for service aboard Navy ships. With nominal engineering effort and the experience garnered from tests on operating all-electric winch drives, it is evident that this system can perform acceptably in accordance with the requirements of the Navy, including reliability and maintainability.

A question to be resolved is which form of the all-electric is the best candidate. The choice is between the DC drives and the AC drives; and the latter are further broken down into the type of inverter power circuit used to supply the AC motor:

Variable Voltage Inverter
Pulsewidth Modulated Inverter
Current-Source Inverter

Performance predictions relating to the above drives are given in Table 1.

TABLE 1 - ALL-ELECTRIC DRIVE SYSTEMS PERFORMANCE PREDICTIONS

	Service Requirement	Performance Prediction (1 to 5 rating)*			
		DC Drive	AC Drive		
			Voltage Source	Current Source	PMW
Overall Performance					
Rated Full Load	9,072 kg @ 1.219 m/s	5	5	5	5
Max. Overload	13,608 kg @ .609 m/s	4	4	5	5
Rated Cable Speed	1.219 m/s	5	5	5	5
Minimum Cable Speed	0.122 m/s	5	5	5	5
Bidirectional Operation	Required	5	5	5	4
Regenerative Operation	Required	3	4	5	1
Mission Profile	(See Fig. 1-2)	4	4	4	3
Off-the-Shelf Industrial Item	Required	5	4	4	4
Multiple Source	At least two	5	4	4	1
Motor-Controller Interchangeability	Desired	2	1	2	5
Reliability and Maintainability					
1. Reliability	1,500 hr MTBF minimum	5	5	5	5
2. Maintainability	2 hr MTTR maximum	5	5	5	5
Ease of Maintenance	Desired	5	5	5	5
Built-in Test Features	Desired	5	5	5	5
EMI and Line-Notching	Minimized	3	4	4	3
Overload Response	Nondestructive	4	4	5	1
Minimum System-Response Time	1-3 s	2	3	4	5
Average System Efficiency	75-90 percent	4	3	3	5
Cost	$20,000-30,000 per system	4	4	4	1
System Weight	680 kg - maximum	3	3	3	2

*Rating Code: 5 is superior, 4 is good, 3 is average, 2 is below average, and 1 is poor.

As for the choice of motors, the polyphase induction machine is perhaps the simplest in construction and the most rugged of all the motors used in industrial processes. (See Technical Reference 6.) Within the past decade the design of AC motor speed controls has progressed to the point where the AC controller/motor is economically an attractive drive. Presently, the AC system is ideal for service where space requirements exclude the larger and heavier DC motor, where inaccessibility of the motor or adverse environments rule out brushes and commutators, or when a high motor speed is required.

In summary, since the AC system uses a relatively inexpensive motor, it tends towards an economic edge over the DC system under the following conditions:

1. A watertight motor is required.
2. Frequent reversing and/or controlled slowdown requires a regenerative power unit (as in the case of the winch drive).

Although the table shows that the predicted performance of all the DC and AC drives (including the Voltage-Source, Pulsewidth Modulated, and Current-Source/Slip-Regulated (CS/SR) AC drives) generally meet the overall winch-system requirements of all the AC drives, the CS/SR drive is definitely superior for winch service since it best satisfies the critical regeneration and overload requirements. Accordingly, the CS/SR drive is selected as the one whose predicted performance shall most closely match the Navy's needs, including reliability and maintainability.

MOTOR/CONTROLLER INTERCHANGEABILITY

A motor/controller interchangeability program is needed to elicit from motor manufacturers specific definitions of critical electrical motor parameters pertinent to matching a motor to a controller on at least one product line of integral horsepower motors. It is expected that under this program no effort will be made to either standardize these parameters or decrease manufacturing tolerances. Instead, the main thrust will be to have the critical motor electrical parameters together with their tolerances readily available to all controller producers so that compatible

controllers can be designed and fabricated independently to match any given manufacturer's motor. Controller design engineers are currently being asked to list their requirements for the essential electrical motor parameters needed to mate the motor to the controller.

TORQUE AND SPEED

Torque, speed, horsepower-rating of the motor, and speed of response of the winch system are interrelated. For a typical system in which the inertia (WK^2) is about 97.8 $lb\text{-}ft^2$ (4.12 $kg.m^2$) (mostly in the motor), it was found that the time to accelerate the full rated load from zero to full speed with the load traveling at maximum speed is less than one second, neglecting the effects of gear backlash and gear moments of inertia. This is even quicker in the case of the AC motor, since the AC motor has a rotor inertia approximately one-third of the rotor inertia of the DC motor with its heavy wire wound armature.

MOTOR/CONTROLLER TEMPERATURE RATINGS

The motor/controller maximum temperature ratings limit the successful operation of both the motor and the thyristors in the controller. These temperature ratings will be established during the testing of a prototype system. An ambient temperature of 50 C has been selected initially as a "worst-case" operational parameter. Also "hot spot"/ambient temperature sensors will be installed in all candidate motor/controller prototype packages for evaluation and possibly installed as a special modification in a "hardened" system package for Navy installation. These temperature sensors together with cooling fan sensors may ultimately become a part of the protective/alarm equipment of the final "hardened" system.

Both the motor and controller shall be specified with internal, factory-installed, "hot-spot" thermocouple temperature sensors. Manufacturers shall be requested to supply "maximum temperature/time" and "overload current/time limit damage" curves for these equipments. The interaction of the shipboard environment and the actual winch duty profiles with

both the motor and the controller will ultimately determine the specifications of the audio-visual, over-temperature alarm system.

ENVIRONMENTAL FACTORS

While the industrial Controller/Motor drive producers routinely design their systems for service in the relatively hostile environments existing in steel and textile mills, chemical plants, and locomotive traction installations, no off-the-shelf all-electric drives are currently available specifically for service aboard naval, ocean-going ships. (All-electric winch drives are, however, presently finding limited use aboard commercial lake and river craft.)

As a result of the lack of military AC or DC all-electric drives, it shall be necessary to provide a below deck installation for the controller that shall be resistant to wide temperature variations, vibration, and ship's motion. In addition, provision shall further have to be made to protect the other electric and electronic equipments aboard from the line-notching and EMI/RFI effects that are generated by the SCR, all-electric drives. It is conceivable that the use of an isolation transformer along with the judicious choice of a primary AC power circuit will reduce the line-notching effects to a tolerable level; and that the controller enclosure can contain the additional EMI/RFI filtering to suppress unwanted harmonic output, before it can interfere with the radars and communication equipment aboard.

RELIABILITY PREDICTIONS

Reliability predictions developed per the MIL-HDBK-217B methodology and constructed from data furnished by manufacturers of both AC and DC Drives predict a Mean-Time-Between-Failure (MTBF) of 5,080 hr for an industrial version of the DC Drive and a MTBF of 23,413 hr for a military model of the AC Drive. (See Appendix D for the detailed development of the Reliability Predictions.) It is important to note, however, that the inherent reliability of the DC Drive with upgraded solid-state component

parts approaches parity with the AC Drive (military version). This ability of the controller designer to effectively determine the inherent reliability of an all-electric system is an important attribute of this system.

MAINTAINABILITY PREDICTION METHODOLOGY

The Maintainability Prediction for the All-Electric Winch Drive System is prepared in accordance with the methodology and procedures outline in MIL-HDBK-472, Maintainability Prediction. The Mean Time to Repair (MTTR) Analysis and Calculations are shown in Table 2, MTTR Analysis Sheet for the AC Drive, and Table 3, MTTR Analysis Sheet for the DC Drive. The predicted Arithmetic Mean Time to Repair (MTTR) is 1.7 hr for the AC Drive System and 1.8 hr for the DC Drive System for repair times assuming a normal distribution.

The bases for determining the part failure rates in Table 2, MTTR Analysis Sheet for the AC Drive are:

1. The AC Motor failure rate of 0.800 failures per 10^6 hr calculated in this report's Appendix D (Motor Failure Rate Methodology), is proportioned between the Rotor Bearings and the Stator Windings per the ratio 3.37:1, based upon detailed reliability predictions made on a 125-hp squirrel-cage induction motor, designed to operate within a naval shipboard environment.

2. The Isolation-Transformer, Operator-Control, and Controller failure rates are per this report's Appendix D (MTBF Prediction).

Part failure rate considerations applicable to Table 3, MTTR Analysis Sheet for the DC Drive, are:

1. The total DC Motor failure rate of 5.649 failures per 10^6 hr calculated in Appendix D (Motor Failure Rate Methodology), is proportioned between the Field and Armature Windings and the Bearings and Brushes and Holders per the same ratio of 3.37:1 used for the AC Motor. In addition, the failure rates are divided equally between the Field and Armature windings as well as between the Bearings and Brushes and Holders.

TABLE 2 - MTTR ANALYSIS SHEET FOR AC DRIVE

Part Ident-ification	Circuit Designa-tion	λp Failure Rate	Average Time (hours) to Perform Repair Task (Rp)							SUB-TOTAL Rp	λpRp
			Locali-zation	Isola-tion	Disas-sembly	Inter-change	Reassem-bly	Align-ment	Check-out		
Stator	Winding	0.183	0.25 for both		0.5	5.0	0.5	0.25 for both		6.50	1.190
Rotor Bearings		0.617	0.25 for both		1.5	3.0	1.5	2.0 for both		8.25	5.090
Isolation XFMR		1.296	0.35 for both		0.4	1.0	0.4	0.12 for both		2.27	2.942
Operator Control		9.401	0.12 for both		0.3	0.5	0.3	0.4 for both		1.62	15.230
AC Controller		31.215	0.50 for both		0.2	0.5	0.2	0.2 for both		1.60	49.944
		$\Sigma\lambda p$ 42.712 failures/10^6								$\Sigma\lambda pRp$	74.396

MTTR = $\Sigma\lambda p\ Rp/\lambda p$ = 74.396/42.712 = 1.742 hr

TABLE 3 - MTTR ANALYSIS SHEET FOR DC DRIVE

Part Ident-ification	Circuit Designa-tion	λp Failure Rate	Average Time (hours) to Perform Repair Task (Rp)							SUB-TOTAL Rp	$\lambda p Rp$
			Locali-zation	Isola-tion	Disas-sembly	Inter-change	Reassem-bly	Align-ment	Check-out		
Field	Winding	0.647	0.25 for both		0.5	5.0	0.5	0.25 for both		6.50	4.206
Armature	Winding	0.648	0.25 for both		0.5	2.5	0.5	0.25 for both		4.00	2.592
Bearings		2.177	0.25 for both		1.5	3.0	1.5	2.0 for both		8.25	17.960
Brushes and Holders		2.177	0.25 for both		1.5	3.0	1.5	2.0 for both		8.25	17.960
Isolation XFMR		1.296	0.35 for both		0.4	1.0	0.4	0.12 for both		2.27	2.942
Operator Control		9.401	0.12 for both		0.3	0.5	0.3	0.4 for both		1.62	15.230
DC Controller		180.501	0.50 for both		0.2	0.5	0.2	0.2 for both		1.60	288.802
		$\Sigma\lambda p$ 196.847 failures/10^6								$\Sigma\lambda p Rp$	349.692

MTTR = $\Sigma\lambda p\ Rp/\lambda p$ = 349.692/196.847 = 1.776 hr

2. The Isolation-Transformer, Operator-Control, and Controller failure rates are per Appendix D (MTBF Prediction).

The Average Time to Perform Repair Task estimates are based upon the maintenance factors discussed in the following paragraph. For example, it is evident from the lengthy procedure for disassembly and reassembly of the motor that the 6-hr estimate is reasonable for disassembly, interchange, and reassembly of the stator. Also it is important to note that the motors require relatively high maintenance times, despite their relatively low failure rates.

As more detailed Controller and Motor data becomes available, such as the specific maintenance information found in Operating, Maintenance and Repair Manuals, the estimated average times to perform repair tasks shall become correspondingly more definitive.

General

A basic measure of maintainability is the Equipment Repair Time (ERT) expressed in hours or (minutes). The ERT is defined as the median of individual repair times and is expressed by specific formulations for various statistical distributions, such as the following one:

When repair times follow a normal distribution the basic parameter of measure is the Mean Time to Repair (MTTR). Since for this distribution, the median is equal to the mean, the MTTR is a satisfactory measure of the true ERT. The ERT is therefore equal to the MTTR and is expressed as follows:

$$ERT = \frac{\Sigma(\lambda Rp)}{\Sigma\lambda} = MTTR$$

where λ = average part failure rate in failures per 10^6 hr and Rp = repair time required to perform a corrective maintenance action in hours

Controller Maintenance

The repair time estimates and calculations take into consideration the design features and built-in test equipment and trouble-shooting instrumentation, alarms, and indicators in the system. The AC Controller and the DC Controller have circuit board assemblies that are readily replaceable as complete modules leaving relatively few component parts to be checked for malfunction. Many of the following maintenance and repair aids are found in currently-available controllers:

1. Hinged printed circuit board mountings for easy access to other component parts
2. Monitoring meters for instant visual indication of drive operation
3. Modular construction for minimizing down-time and simplifying repair
4. Below 30-V control circuits for protection of service personnel
5. Electronic assemblies are isolated and groundable. (Operational amplifiers and common-mode rejection techniques eliminate high-energy inputs and isolate the electronic portion of the system.)
6. Inverters in some designs attempt to operate with a malfunctioning power or control circuit thereby offering the capability of running while undergoing de-bugging and servicing
7. Test module identifies failed electronic modules and checks for the presence and modulation of SCR firing pulses by guiding maintenance personnel via a plastic laminated, magnetized procedure chart
8. Diagnostic panel for pre-startup check and maintenance during the life of the equipment
9. Circuit Monitor and thumbwheel selector switch with master test points for checking printed circuit boards with probes
10. Plug-in relays
11. All adjustments are non-interacting and on single plug-in adjustment board

12. Accessible on-site replacement of SCR Thyristor diodes without replacing or removing heatsinks

13. Color-coded test module meter indication and charted procedure helps identify failed module and pin-points the malfunctioning part

14. Torque wrench not required to change thyristors

Standard protection circuits in a typical motor-controller include:

Magnetic Trip Line Circuit Breaker - provides positive disconnecting means and short-circuit protection. Interrupts all three phases. No line fuses to replace.

Static Over-Current Trip - trips drive off line safely and rapidly. Inhibits further firing of thyristors in fault current situations.

Low-Voltage Protection - provided by AC line fault relay which de-energizes the drive under low voltage conditions, preventing restarting automatically.

Phase Loss Protection - drive stops in the event a phase is lost. Electronic circuits continue to function in a single phase mode for orderly shutdown.

Line Surge Protection - surge suppressors and RC networks provide voltage transient protection.

Load-Break Loop Contactor - interrupts full load current in the event the thyristor bridge is not phased back.

D-C Loop Protection - on DC Controllers, overload relay provides overtemperature protection for the motor and the wiring. A loop fuse is included for fault current protection.

Bridge Protection - DC current limit, overtemperature switch on heat-sink and line reactors provide bridge protection. Line reactors are non-saturating wound iron-core type. Limit faults, provide recovery current control and di/dt protection, plus reduced line noise.

Speed Loss Sensor - detects overloading condition on the motor and causes shutdown at a present value.

Current Limit Circuit - allows operation into a short-circuit of the inverter in servicing modes to facilitate location of failed components.

AC Motor Maintenance

The 3-phase, squirrel-cage AC Induction Motor is the smallest and lightest electrical motor available for winch drive service and requires a minimum of maintenance, since it has no slip-ring, commutator and brushes to maintain. A single moving part, the rotor, has a shaft that is supported at both ends with long-life bearings. The induction motor rotor is an integrally cast element that locks in special steel laminations to form a solid metal cage.

Conditions which constitute failure of an AC Motor are: bearings - poor maintenance procedure on bearings and/or lack of lubrication at designated times resulting in noisy bearings, and stator windings - exposure to unreasonable environmental conditions of moisture and contamination resulting in low-insulation resistance.

The following typical AC Motor maintenance factors support the estimated repair times chosen for each corrective maintenance action:

1. General - insulation resistance should be checked periodically. Whenever insulation resistance drops to 25 megohms, it is recommended that a complete check be made of the machine.

2. Rotor - the rotor is an indestructible squirrel cage and, therefore, requires no maintenance.

3. Stator Windings - stator coils should be cleaned regularly and should occasionally be thoroughly dried and varnished, in accordance with general instructions.

4. Lubrication - lubrication intervals depend wholly on the operating conditions and the bearings used. In light service, bearings can sometimes go for six to nine months and, in some cases, can be left entirely alone except for yearly cleaning and re-lubrication.

On heavier duty service where conditions are less favorable, such as high speeds and high temperatures, bearings may require to be lubricated

much more frequently. It is good practice, where operating temperatures are approximately 80 C, to add fresh lubricant weekly in limited quantities depending upon the size of the bearing.

Constant high heat will evaporate part of the oil from the lubricant requiring frequent re-applications of new lubricant to keep the oil replenished.

5. Disassembly and Assembly of Motor - typical motor disassembly and assembly instructions per the maintenance manual are followed.

6. Trouble Shooting - when trouble is experienced, the motor is isolated from the driven winch and tested separately in order to isolate the cause of the trouble. A troubleshooting chart helps locate the cause of the malfunction and indicates the corrective action to be taken.

DC Motor Maintenance

The DC Motor requires all the attention paid to the AC Motor plus considerable additional effort for servicing the armature windings, commutator, brushes and brush holders. This extra work is reflected in the estimated times shown in Table 3.

Operator Control Maintenance

Little time is expended on the Operator Control maintenance due to the presence of relatively few and uncomplicated component parts:

1 each Control potentiometer
6 each Incandescent lamps and holders
1 each 3-pole, double-throw switch

Accordingly, the estimated times shown in Tables 2 and 3 do not exceed 0.5 hr for the average time to perform any particular repair task.

Isolation Transformer Maintenance

Due to the inherent simplicity of the isolation transformer, no repair task exceeds 1.0 hr as shown in Tables 2 and 3. The large size and weight of the transformer do introduce handling problems that must be considered during replacement of the unit.

COST CONSIDERATIONS

Procurement of regenerative AC Controller/Motor and regenerative DC Controller/Motor drives for winch applications in the 150- to 200-hp (152-202-hp metric) size will be favorably priced with respect to the electro-hydraulic winch drive composed of a 200-hp (202-hp metric) induction motor and a hydraulic transmission unit.

As the relatively new all-electric drive technology emerges, initial procurement costs can be expected to become even more competitive. In addition, further savings and increased service flexibility are additional advantages to be expected of the all-electric drives with the prospect that several winch drive motors may eventually be operated independently, but supplied from one basic controller.

The high reliability and ease of maintainability of the all-electric drive predict a low life-cycle cost. With the built-in test equipment and easy replacement of silicon-controlled rectifier (SCR) diodes and printed circuit boards, that currently exemplify good industrial controller-design practice, the availability of the all-electric winch system shall be very high.

TYPICAL MOTOR PRICING

A representative 200-hp (202-hp metric) DC motor that is suitable for service with the regenerative DC Controller costs approximately $20,000 each for a quantity of one each, without the reduction gearing.

A representative 200-hp (202-hp metric) AC motor that is suitable for service with the regenerative AC Controller costs approximately one-third as much, or close to $7,000 each for a quantity of one each, without the reduction gearing.

TYPICAL CONTROLLER PRICING

Typical 200-hp (202-hp metric) regenerative DC Controller pricing ranges from approximately $10,000 each to $15,000 each for a quantity of one each, less the enclosure that adapts the controller for naval marine service.

Representative 200-hp (202-hp metric) regenerative AC Controller pricing is almost twice as great, or approximately $26,500 each for a quantity of one each.

TYPICAL ISOLATION TRANSFORMER PRICING

A representative Isolation Transformer suitable for service with either the AC Controller/Motor drive or the DC Controller/Motor drive has an initial procurement cost of approximately $3,300 each to $5,000 each for a quantity of one each.

TOTAL SYSTEM COST

For the complete system consisting of a motor, controller, and isolation transformer, the combined pricing is as follows: for the DC system $33,300-$40,000 and for the AC system $36,800-$38,500.

INSTALLATION COST CONSIDERATIONS

All-electric winch drive installation costs are expected not to exceed the installation costs for the winches currently in service.

SUPPORT CONSIDERATIONS

Documentation - extensive documentation shall be required due to the introduction of the relatively new all-electric winch drive technology.

Training - preventative maintenance and rapid repair shall be stressed, particularly the use of the built-in test equipment in the controller to diagnose the causes of failure, locate the fault, and the use of rapid-substitution printed-circuit boards and modules to facilitate the repair.

Provisioning/Spares - printed-circuit boards, SCR's, fuses, and other replacement parts and spares shall have to be stocked.

Overhaul - since the electronic portion of the all-electric drives requires no preventative maintenance, its operational availability shall be high. Only the AC motors shall require periodic lubrication and scheduled overhauls. (DC motors require brushes and commutator maintenance in addition to lubrication.)

RECOMMENDED ACTION

As the result of assessing the findings in this cost and feasibility study of All-Electric Winch Drives, it is recommended that:

1. The development of the All-Electric AC Controller/Motor drive design should be further pursued as showing the most promise for the future, particularly since the electric motor is required to operate exposed on the deck.

2. The preliminary development of Navy specifications for the AC Controller/Motor equipment should be initiated with two or more prospective vendors of this equipment.

3. The development of industrial drives using the AC pulsewidth modulation (PWM) controller should be monitored for possible naval service applications as a long-range possibility.

APPENDIX A

ACKNOWLEDGEMENTS

The authors wish to specifically thank the following persons for their invaluable assistance in the acquisition of the myriad of information pieces which went into the construction of this report:

Vernon Ungar and Fred Hill	- Naval Ships Engineering Center (NAVSEC), Washington, D.C.
Eugene Helms and Richard Salo	- Naval Weapons Support Center (NWSC), Crane, IN
James Mills and William Schultz	- Naval Ship Weapon System Engineering Station (NSWSES), Port Hueneme, CA

The authors are also indebted to all of the industrial motor and controller suppliers (Appendix C) that provided the bulk of the information regarding the commercially available drive systems and freely contributed their engineering time and assistance towards the introduction of advanced, solid-state motor control technology into the U.S. Navy.

The contributions made by ASSET Incorporated, particularly by Mr. Sam Levine, in providing the reliability and maintainability analysis and technical writing assistance are hereby also acknowledged.

APPENDIX B

INFORMATION SOLICITATION PACKAGE

DEPARTMENT OF THE NAVY
NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
HEADQUARTERS
BETHESDA, MARYLAND 20034

ANNAPOLIS LABORATORY
ANNAPOLIS, MD. 21402
CARDEROCK LABORATORY
BETHESDA, MD. 20084

IN REPLY REFER TO:
1175:GT
3900

2 SEP 1976

Gentlemen:

The David W. Taylor Naval Ship Research and Development Center has been tasked to determine the feasibility of developing a standard electric winch drive for use in underway replenishment operations aboard auxiliary supply ships. Specifically, our interest is in thyristor controlled electric motors for variable speed winch drives. The installation is such that the motor must be located in an exposed location on the ship's deck, but the controllers would be installed below deck in a protected location.

Once feasibility has been established, the immediate goal of this program is to purchase one or more "standard" controller/motor packages for shipboard evaluation.

In order to conduct our feasibility investigation, we need information to generate sufficiently broad motor controller specifications such that any commercial motor controller of adequate versatility and capacity (Hp) could be adapted to work with one of the specified electric drive motors. We also wish to compare AC and DC drives in this application and thus are interested in AC controllers to operate a 200 hp, Nema B design, AC induction motor, and DC controllers to operate a 200 hp, standard D.C. shunt motor.

The enclosed material - an electric/winch drive system sheet, four (4) mil specs and a winch duty cycle profile-represents the basic technical information regarding the desired winch drive.

We would like you to supply us with information on your commercial motor controllers that will adequately control either of the 200 Hp motors (AC or DC) for this winch drive system.

The information which you furnish to us on your specific motor controller(s) will be used in the feasibility/cost study to evaluate the relative merits of both AC and DC all-electric winch drives for this winch drive application

It is highly desirable that the requested information be provided by 1 October 1976. Material should be mailed to Code 1175 at the Annapolis Laboratory, Annapolis, Maryland 21402. The point of contact is Mr. George W. Turner, telephone (301) 267-2261.

Sincerely,

T. E. Mansfield

T. E. MANSFIELD
Hd. Mobile Support Systems Group
Systems Development Department

Enclosures

Copy to: NAVSEA (Code 935U)
NAVSEC (Code 6164B)

ELECTRIC WINCH DRIVE SYSTEM

Applicable documents (for guidance only):

MIL-W-15808 electric winch   MIL-STD-1399/sec 103 - ships AC power

MIL-W-17265E - winch general   Winch Duty Cycle Profile
MIL-W-17265/1A - winch specific

Desire 2 systems: AC:200 HP AC induction motor drive
DC:200 HP DC shunt motor drive

Basic System: [Controller] — [Motor] — [Gearing (K)] — [Winch Drum]

Controller: Main (thyristor) package to be supplied; must be compatible and function with one of the 2 motor HP ratings given above.
Motor(s): Watertight motors to be furnished by an independent supplier must operate aboard ship in a severe ocean environment, AC:200HP, 460/575 VAC, 3 Ø, 60 HZ, NEMA B, induction motor; DC: 200 HP, Arm, 500 VDC, Field, 240 VDC, shunt wound motor.
Gearing (K): To be specified by controller supplier to match the controller/motor characteristics to the load requirements.
Winch Drum: Mechanical assembly; not to be supplied by the controller supplier.

For each system, please supply information for the following two (2) winch drum loading conditions:

1. Rated Full Load: 20000#, Speed: 240 Ft/Min
2. Maximum Over Load: 30000#, Speed: 120 Ft/Min

Rated cable speed for haul-in or pay-out = 240 ft/min.
Minimum cable speed for haul-in or pay-out = 24 ft/min.
Avg. dia. of cable on winch drum = 35.7 inches
Rated winch drum speed = 24.4 rpm
Gearing ratio (K) = rpm motor/rpm winch drum
Rated Winch HP = 20,000 (240)/33,000 = 145.5 HP

Bi-directional operation of both AC & DC winch systems is required - regenerative controller feature desired.
Give system rise times for step inputs of the two HP. conditions given above, considering total winch drum inertia as 0.15 x motor rotor inertia.

List approximate dimensions and weight of controller package including input isolation, transformer - available ships power: 440 VAC, 3 Ø, 60 HZ.

Provide all available reliability and maintainability data on the controller and other laudatory features of each (AC or DC) controller system.

List cost for basic controller package together with costs of auxiliary (desirable) options.

"Please note that this is a request for information only. It is not an Invitation for bid, it does not obligate the Government in any way, and it does not imply any guarantee for purchase of your product."

APPENDIX C

INDUSTRIAL MOTOR/CONTROLLER SUPPLIERS

Companies solicited for solid-state, industrial, motor/controller packages suitable for use with the highline winch system:

Allen Bradley
T.C.P. Drives, Inc.
213 West Pioneer Road
Cedarburg, Wisconsin 53012

Allis-Chalmers Electrical Systems
P.O. Box 2606
West Allis, Wisconsin 53214

Controls Systems Research
1811 Main
Sharpsburg, Pennsylvania 15215

Cutler-Hammer, Inc.
Industrial Systems Division
4265 North 30th Street
Milwaukee, Wisconsin 53216

Eaton Corporation
Industrial Drives Division
Dynamatic Plant
3122 14th Avenue
Kenosha, Wisconsin 53140

Electric Regulator Corporation
Pearl Street
P.O. Box 698
Norwalk, Connecticut 06852

Emerson Electric Co.
WER Industrial Division
3036 ALT Boulevard
Grand Island, New York 14072

General Electric
Speed Variator Products Operation
Direct Current Motor & Generator Dept.
Erie, Pennsylvania 16531

Louis Allis
Drives & Systems Division
16555 West Ryerson Road
New Berlin, Wisconsin 53151

Power Control Corporation
RIDC Industrial Park
122 Gamma Drive
Pittsburgh, Pennsylvania 15238

Ramsey Controls Incorporated
333 Route 17
Mahwah, New Jersey 07430

Randtronics
150 Constitution Drive
Menlo Park, California 94025

Reliance Electric Company
24701 Euclid Avenue
Cleveland, Ohio 44117

Robicon Corporation
100 Sagamore Hill Road
Plum Industrial Park
Pittsburgh, Pennsylvania 15239

Ross Hill Controls Corp.
1530 West Belt Drive North
Houston, Texas 77043

Westinghouse Electric Corp.
Industrial Equipment Division
P.O. Box 225
Buffalo, New York 14240

APPENDIX D
RELIABILITY AND MAINTAINABILITY PREDICTIONS

The Reliability and Maintainability Predictions are based upon the catalog and instruction manual data made available by the manufacturers of AC and DC Drives and the verbal information gathered from meetings and at plants producing all-electric SCR drives and motors. Figure 6, lists generic parts failure rates for Isolation Transformer, Operator Control, and AC and DC Motors per the MIL-HDBK-217B methodology.

The AC Controller total parts failure rate is extrapolated from the typical MTBF predictions for similar military AC (3-hp and 30-hp) drives. The DC Controller total parts failure rate is determined per MIL-HDBK-217B, Parts Stress Analysis approach, using schematics and photographs in the instruction manual for a standard industrial 200-hp (202-hp metric) DC Controller. The manufacturer's stress factors of sixty to eighty percent are applied. <u>Accordingly, a common basis for comparison does not exist</u>.

Maintainability and Serviceability are analyzed and discussed in general terms stressing vendor-supplied features illustrated in product data sheets and observed close-up during AC and DC Drive demonstrations. As more explicit parts data become available, the predictions can be readily upgraded to more definitive levels.

GENERAL ASSUMPTIONS

The design prediction procedures in MIL-STD-756 and the methodology of MIL-HDBK-217B and the Rome Air Development Center Reliability Design Handbook along with historical and test data and parts failure rates directly available from the manufacturers of the component parts are used to build Reliability and Maintainability Predictions. In order to employ the methodology directly, the following General Assumptions apply:

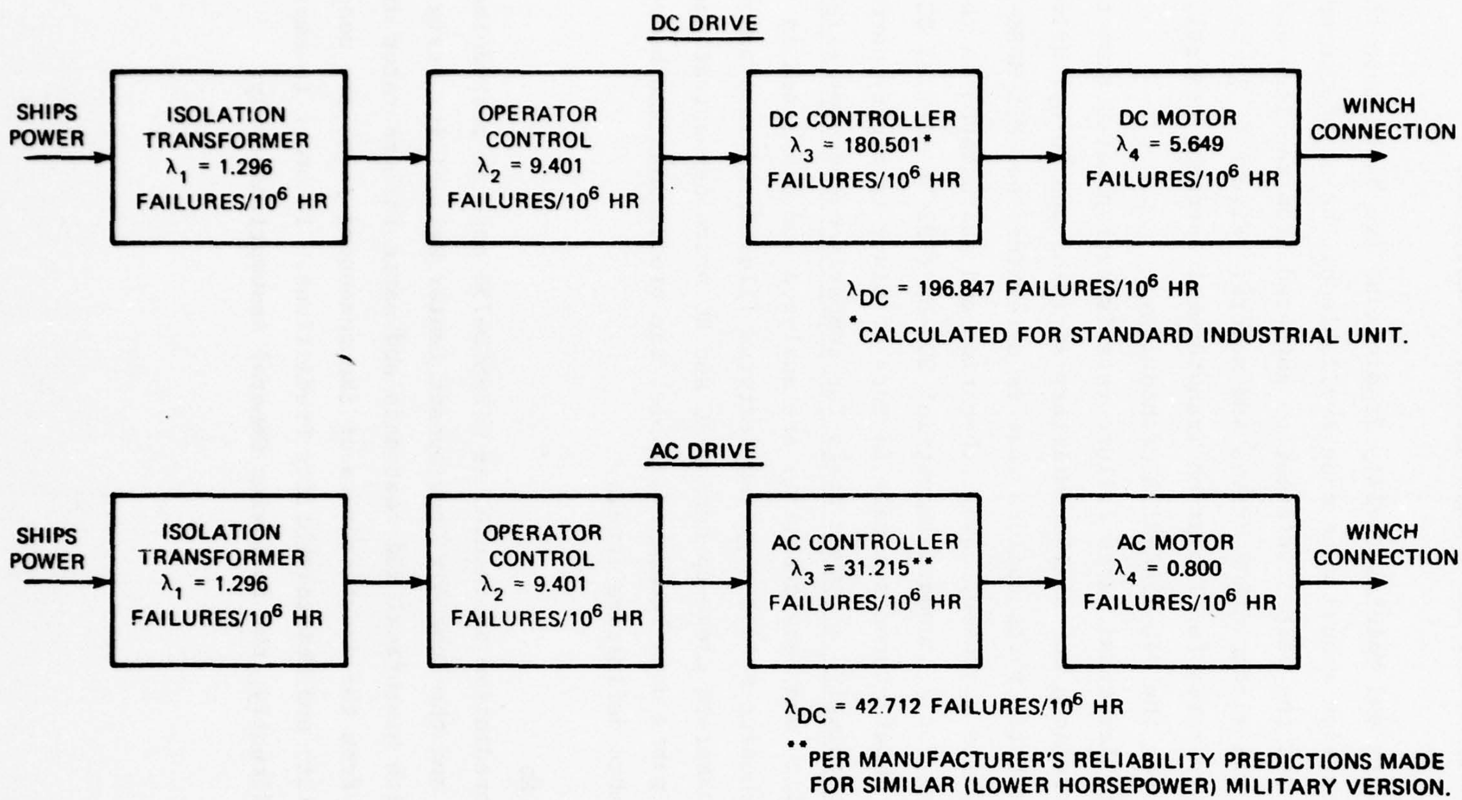


Figure 6 - All-Electric Winch Drive Reliability Block Diagram

1. No occurrence of simultaneous failures

2. No cascading of failures

3. No parts are overstressed

4. Failure of any part that causes the system to operate outside the specified performance limits shall constitute a system failure

RELIABILITY BLOCK DIAGRAM

A necessary step in building a Reliability and Maintainability Prediction is organizing the Reliability Block Diagram, which serves the following functions:

1. Categorizes the system in terms of major Reliability and Maintainability blocks

2. Highlights the existence of system redundancy and parallel paths that improve the reliability of the system

3. Graphically shows how the total system failure rate is distributed among the individual system components

The All-Electric Winch Drive Reliability Block Diagram is shown in Figure 6. It is derived from the System Block Diagram, and represents the systematic arrangement of functions that must be performed and the sequence in which they must be performed for successful operation. Successful operation of the system represented by the block diagram is predicated on success of the individual parts. Assumptions that apply to the reliability block diagram per MIL-STD-756 are:

1. The lines connecting the blocks have no reliability values, and serve only to give order and direction to the diagram

2. Failure of any part or combination of parts denoted by a block in the diagram will cause failure of the entire system provided the specified performance limits have been exceeded

3. Each functional entity denoted by a block in the diagram is independent with respect to probability of failure from all other blocks

4. Operator or maintainer-induced failures are not considered

RELIABILITY MATH MODEL

The All-Electric Drive Reliability Block Diagram for both the AC and the DC Drives shown in Figure 6 represents a series reliability configuration for either AC or DC Drives with no redundant paths. Thus, the total parts failure rate for the entire system is the sum of the individual block part failure rates.

Accordingly, the Reliability Math Model is the product of the individual block probabilities:

$$R_{TOTAL} = R_1 \; R_2 \; R_3 \; . \; . \; . \; R_n$$

where $R = e^{-\lambda t}$ and $R_{TOTAL} = e^{-\lambda_1 t} \; e^{-\lambda_2 t} \; e^{-\lambda_3 t} \; . \; . \; . \; e^{-\lambda_n t}$

For a series reliability model such as the All-Electric Winch Drive System, the failure rates can be summed, assuming an exponential system failure rate and a random occurrence of failures. Therefore:

$$\lambda_{TOTAL} = \lambda_1 + \lambda_2 + \lambda_3 \; . \; . \; . \; . \; + \lambda_n$$

Furthermore, the Mean-Time-Between-Failures (MTBF) for the System becomes:

$$MTBF = 10^6 \text{ hours}/\lambda_{TOTAL}$$

FAILURE RATE METHODOLOGY

The parts failure rates of the component parts of the system are calculated per the methodology and procedures given in MIL-HDBK-217B wherever possible. Part and component failure rate calculations for typical component parts in SCR power supplies undergoing conservative circuit stress conditions are provided in Failure Rate Data Sheets shown in Figures 7

PART CLASS	DIODE	DIODE
PART TYPE	RECTIFIER	RECTIFIER
PART TYPE NO.	JAN 1N4246	2N692
DESCRIPTION	SILICON	Si THYRISTOR
MIL-SPECIFICATION	S-19500/286	---
MFGR. DWG. NO.		
GROUP	IV	IV
INSULATION CLASS		
MAX. RATED TEMP.	160 C	125 C
APPL. VOLTAGE		
PWR. DISSIPATED		
C.F.	1.0 (p. 2.2.9-6)	0.667 (7d.)
ELEC. STRESS RATIO (S)	0.02 (USE 0.1)	0.053 (USE 0.1)
π_{eff}. ELEC. LOADING		
AMBIENT TEMP.		
CASE TEMP.	50 C	55 C
TEMP. RISE		
T_{HS}		
F.R. REFERENCE	TABLE 2.2.4-6	TABLE 2.2.6-3
λ_b, BASE F.R.	0.0016	0.0061
FACTORS		
π_E, ENVIRONMENTAL	25	25
π_f, FAMILY TYPE		
π_A, APPLICATION	1.0 (SMALL SIG.)	N/A
π_Q, QUALITY	5.0	25
π_C, CONSTRUCTION	1.0	N/A
π_V, VOLTAGE		
π_{S_2}, VOLT. STRESS	0.70 (S_2 = 18 PERCENT)	N/A
π_C, COMPLEXITY		
π_R, RESISTANCE		
π_{TAPS}, POT.		
λ_{bE}, ACT. ASSY.		
πno. OF CONTACTS		
λ_{bG}, OPS./HR F.R.		
π_{CYC}, CYCLING RATE		
λ_p, PART F.R./10^6 HR	0.140 EA.	3.813 EA.

Figure 7 - Failure Rate Data Sheet - Diodes

PART CLASS	RESISTOR
PART TYPE	1000/3W
PART TYPE NO.	RW79U1001F
DESCRIPTION	WW, FIXED, PAPER
MIL-SPECIFICATION	R-26
MFGR. DWG. NO.	
GROUP	
INSULATION CLASS	
MAX. RATED TEMP.	
APPL. VOLTAGE (VOLTS)	24.4
PWR. DISSIPATED	0.595
C.F.	
ELEC. STRESS RATIO (S)	0.198
π_{eff}, ELEC. LOADING	
AMBIENT TEMP.	50 C
CASE TEMP.	
TEMP. RISE	
T_{HS}	
F.R. REFERENCE	2.5.3-8
λ_b, BASE F.R.	0.0049
FACTORS	
π_E, ENVIRONMENTAL	7 (N_S)
π_f, FAMILY TYPE	
π_A, APPLICATION	
π_Q, QUALITY	5
π_C, CONSTRUCTION	
π_V, VOLTAGE	
π_{S_2}, VOLT. STRESS	
π_C, COMPLEXITY	
π_R, RESISTANCE	1.0
π_{TAPS}, POT.	
λ_{bE}, ACT. ASSY.	
πno. OF CONTACTS	
λ_{bG}, OPS./HR F.R.	
π_{CYC}, CYCLING RATE	
λ_p, PART F.R./10^6 HR	0.172

Figure 8 - Failure Rate Data Sheet - Resistors

PART CLASS	TRANSFORMER
PART TYPE	SAT. TRANS.
PART TYPE NO.	BE 14573-001
DESCRIPTION	
MIL-SPECIFICATION	E-917
MFGR. DWG. NO.	(T-27)
GROUP	
INSULATION CLASS	A
MAX. RATED TEMP.	
APPL. VOLTAGE	
PWR. DISSIPATED	
C.F.	
ELEC. STRESS RATIO (S)	
π_{eff}. ELEC. LOADING	
AMBIENT TEMP.	50 C
CASE TEMP.	
TEMP. RISE	50 C
T_{HS}	105 C
F.R. REFERENCE	TABLE 2.7-6 (MIL-T-27/MIL-C-15305 CLASS)
λ_b, BASE F.R.	0.0108
FACTORS	
π_E, ENVIRONMENTAL	5.0
π_f, FAMILY TYPE	8.0
π_A, APPLICATION	
π_Q, QUALITY	
π_C, CONSTRUCTION	
π_V, VOLTAGE	
π_{S_2}, VOLT. STRESS	
π_C, COMPLEXITY	
π_R, RESISTANCE	
π_{TAPS}, POT.	
λ_{bE}, ACT. ASSY.	
πno. OF CONTACTS	
λ_{bG}, OPS./HR F.R.	
π_{CYC}, CYCLING RATE	
λ_p, PART F.R./10^6 HR	0.432 EA,

Figure 9 - Failure Rate Data Sheet - Transformers

PART CLASS	RESISTOR
PART TYPE, WW, Ω/w	2k/12.5
PART TYPE NO.	FORM EW
DESCRIPTION	VARIABLE
MIL-SPECIFICATION	R-15109*
MFGR. DWG. NO.	
GROUP	
INSULATION CLASS	
MAX. RATED TEMP.	
APPL. VOLTAGE (VOLTS)	0.2
PWR. DISSIPATED (W)	<0.001
C.F.	
ELEC. STRESS RATIO (S)	<0.1
π_{eff}. ELEC. LOADING	
AMBIENT TEMP.	50 C
CASE TEMP.	
TEMP. RISE	
T_{HS}	
F.R. REFERENCE	2.5.5-20
λ_b, BASE F.R.	0.087
FACTORS	
π_E, ENVIRONMENTAL	17.5
π_f, FAMILY TYPE	
π_A, APPLICATION	
π_Q, QUALITY	2.0
π_C, CONSTRUCTION	1.0
π_V, VOLTAGE	1.1
π_{S_2}, VOLT. STRESS	
π_C, COMPLEXITY	
π_R, RESISTANCE	1.0
π_{TAPS}, POT.	1.0
λ_{bE}, ACT. ASSY.	
πno. OF CONTACTS	
λ_{bG}, OPS./HR F.R.	
π_{CYC}, CYCLING RATE	
λ_p, PART F.R./10^6 HR	3.350

*MIL-R-22 FAILURE RATES USED FOR MIL-R-15109 VARIABLE RESISTORS.

Figure 10 - Failure Rate Data Sheet - Wire Wound Resistors

through 10. Deviations from MIL-HDBK-217B are noted on the Failure Rate Data Sheets as well as in the discussions of the component parts.

A detailed failure rate analysis requires separate failure-rate sheets for each part of the system. Since specific and complete part descriptions and individual part stress information is not readily available from suppliers at this phase of system development, the reliability analysis shall depend mainly upon available MTBF data on a similar AC Drive system and by derivation from the schematics, photographs, and text in the DC Controller Instruction Manual for a standard industrial 200-hp (202-hp metric) unit.

SEMICONDUCTOR FAILURE RATE METHODOLOGY

The failure rates of the semiconductor devices including low power and high-power rectifier diodes, silicon-controlled rectifier (SCR) diodes, voltage-regulation (zener) diodes, and NPN and PNP transistors are determined according to the detailed procedures in MIL-HDBK-217B. The general failure rate model for diodes and transistors is:

$$\lambda_p = \lambda_b \left(\pi_L \pi_A \pi_Q \pi_{S_2} \pi_C\right) \text{ failures}/10^6 \text{ hr}$$

where λ_p = part failure rate

λ_b = base failure rate usually expressed by a model relating the influence of electrical and temperature stresses on the part

π_E = environmental factor that accounts for the influence of environmental factors other than temperature. For a Sheltered Naval environment (surface ship conditions) subject to occasionally high shock and vibrations), symbol is N_S

π_A = application factor that accounts for application in terms of circuit function

π_Q = quality factor that accounts for the effects of different quality levels. It varies according to whether the device is JANTXV, JANTX, JAN, or lower.

π_{S_2} = stress factor that adjusts the reliability model voltage stress in addition to the wattage included in λ_b

π_C = construction factor that accounts for whether the device is metallurgically bonded or employs spring-loaded contacts

As an example, the failure rate for a JAN 1N4246 diode per Figure 7 is found to be 0.140 failures per million hours.

In a similar manner, MIL-HDBK-217B is used for Thyristors (Group VI), whose part failure rate model is: $\lambda_p = \lambda_b \lambda_Q \lambda_E$ failures/10^6 hr. The failure rate for the Type 2N692, a typical SCR Thyristor, is 3.813 failures per 10^6 hr.

The zener diodes (Group V) parts failure rate model is:

$$\lambda_p = \lambda_b \pi_E \pi_A \pi_Q \text{ failures}/10^6 \text{ hr}$$

The part failure rate model for Transistors is:

$$\lambda_p = \lambda_b \pi_E \pi_A \pi_Q \pi_{S_2} \pi_C \text{ failures}/10^6 \text{ hr}$$

RESISTOR FAILURE RATE METHODOLOGY

The failure rates of fixed, wirewound, adjustable/variable resistors and rheostats are determined according to the detailed procedures in MIL-HDBK-217B. The general part failure rate for resistors is:

$$\lambda_p = \lambda_b \pi_E \pi_R \pi_Q \text{ failures}/10^6 \text{ hr}$$

The general model for variable resistors is:

$$\lambda_p = \lambda_b \pi_{TAPS} \pi_R \pi_V \pi_C \pi_E \pi_Q \text{ failures}/10^6 \text{ hr}$$

where π_{TAPS} = tap connections factor on potentiometers that accounts for the effect of multiple taps on the resistance element

π_V = voltage factor that accounts for voltage effects

π_C = construction factor that accounts for variable resistor construction class

INDUCTIVE DEVICES FAILURE RATE METHODOLOGY

The general failure rate model for inductive devices (inductors, transformers, magnetic amplifiers, reactors) is:

$$\lambda_p = \lambda_b \, \pi_E \, \pi_F \text{ failures}/10^6 \text{ hr}$$

where π_F = family type factor.

For Type A insulation, the base failure rate is: λ_b = 0.0108 failures/10^6 hr; and the part failure rate is:

$$\lambda_p = 0.432 \text{ failures}/10^6 \text{ hr}$$

MOTOR FAILURE RATE METHODOLOGY

From MIL-HDBK-217B, the failure rate model for high speed motors is:

$$\lambda_p = (\lambda_E + \lambda_W) \, \pi_E \text{ failures}/(10)^6 \text{ hr}$$

where λ_E = electrical failure rate = $\lambda_b \, \pi_F$

λ_W = mechanical failure rate = $\dfrac{P_{pop} \, (10)^4}{top}$

λ_b = electrical base failure rate

π_F = motor family and quality factor

t_{op} = motor operating time (hr) for which λ_p is to be calculated

p_{pop} = percentage of motor mechanical failures during operating period, t_{op}

π_E = environmental factor

For the Three-Phase Motor:

$$\lambda_p = 0.800 \text{ failures}/10^6 \text{ hr}$$

For the Commutator-Type Motor:

$$\lambda_p = 5.649 \text{ failures}/10^6 \text{ hr}$$

SWITCH FAILURE RATE METHODOLOGY

The part failure rate model for switches is:

$$\lambda_p = \lambda_b(\pi_E \pi_C \pi_{CYC}) \text{ failures}/10^6 \text{ hr}$$

where λ_b = base failure rate model

π_E = environmental factor

π_C = contact form and quantity factor

π_{CYC} = switching cycles per hour factor

For 20,000 life operations and a MIL-SPEC Pushbutton Switch, the part failure rate is:

$$\lambda_p = 0.051 \text{ failures}/10^6 \text{ hr}$$

MTBF PREDICTION

The total parts failure rate of each block comprising the Drives shown in Figure 6 is determined by:

Isolation Transformer - the 0.432 failures/10^6 hr per the calculation in paragraph entitled Inductive Devices Failure Rate Methodology is multiplied by three (3-phase, 3-transformer configuration) to obtain:

$$\lambda_1 = 1.296 \text{ failures}/10^6 \text{ hr}$$

Operator Control - the Operator Control consists of the control potentiometer, six indicator lamps ("Trouble," "Converter Hot," "Transformer Hot," "Motor Hot," "Power Available," "Power On"), and a Pushbutton 3PDT Switch.

The control potentiometer part failure rate is 3.350 failures/10^6 hr per Figure 10 of this report, for a typical variable resistor that is conservatively loaded.

From Table 2.13-1, MIL-HDBK-217B, AVERAGE FAILURE RATES FOR MISCELLANEOUS PARTS, the part failure rate for Incandescent Lamps is 1.000 failures/10^6 hr, or 6.000 failures/10^6 hr for the six lamps.

From paragraph entitled Switch Failure Rate Methodology, the part failure rate for a Pushbutton 3-pole, double-throw (3PDT) Switch is 0.051 failures/10^6 hr. The total parts failure rate for the Operator Control is therefore:

$$\lambda_2 = 3.350 + 6.000 + 0.051 = 9.401 \text{ failures}/10^6 \text{ hr}$$

AC Controller - the AC Drive Controller is assumed to have a total parts failure rate based upon the following considerations:

1. A manufacturer's calculated prediction of 32,036 hr MTBF for a 30-hp conservatively designed military AC Controller.

2. The assumption that increasing the horsepower rating from 30-hp to approximately 200-hp does not appreciably increase the part failure rate provided the individual parts are stressed proportionately the same in both designs.

Accordingly, the Controller part failure rate for the AC Controller is:

$$\lambda_3 = 10^6/32,036 = 31.215 \text{ failures}/10^6 \text{ hr}$$

DC Controller - without a detailed parts failure prediction from manufacturers of the DC Controller, the reliability prediction is constructed from the data available in the instruction manual for a standard DC Controller (200-hp) and from the manufacturer's stress factors and design philosophy. The part failure rate breakdown is per Figure 11.

AC Motor - per paragraph entitled Motor Failure Rate Methodology, the failure rate for the AC Motor is:

$$\lambda_4 = 0.800 \text{ failures}/10^6 \text{ hr}$$

DC Motor - per paragraph entitled Motor Failure Rate Methodology, the part failure rate for the DC Motor is:

$$\lambda_4 = 5.649 \text{ failures}/10^6 \text{ hr}$$

The total All-Electric Drive parts failure rate prediction is the sum of the individual block failure rates as shown in Figure 6:

DC DRIVE	
Isolation Transformer	$\lambda_1 = 1.296$
Operator Control	$\lambda_2 = 9.401$
DC Controller	$\lambda_3 = 180.501$
DC Motor	$\lambda_4 = 5.649$
Total DC Drive (Industrial Model)	$\lambda_{DC} = 196.847 \text{ failures}/10^6 \text{ hr}$

QUANTITY	ITEM	REFERENCE	FAILURES PER 10^6 HOURS
1	MAIN PRINTED CIRCUIT BOARD (PCB)	SCHEMATIC DIAGRAM	111.333
4	GATE FIRING PCB	PHOTOGRAPH	5.232
1	REFERENCE AND ACTUATOR PCB	PHOTOGRAPH	1.670
1	POWER SUPPLY PCB	TYPICAL DESIGN	1.037
4	TRANSFORMER	SCHEMATIC DIAGRAM	2.592
2	ZERO CURRENT DETECTOR PCB	ESTIMATED FROM PHOTOGRAPH	2.990
1	TWELVE-SCR RECTIFIER BRIDGE	SCHEMATIC DIAGRAM	48.051
1	BLOWER	SCHEMATIC DIAGRAM	7.596
		TOTAL PARTS FAILURE RATE – DC CONTROLLER	180.501

Figure 11 - DC Controller Parts Failure Rates

AC DRIVE

Isolation Transformer	λ_1	$= 1.296$
Operator Control	λ_2	$= 9.401$
AC Controller	λ_3	$= 31.215$
AC Motor	λ_4	$= 0.800$
Total AC Drive (Military Model)	λ_{AC}	$= 42.712$ failures/10^6 hr

The predicted Mean-Time-Between-Failures for the DC Drive ($MTBF_{DC}$) is therefore:

$$MTBF_{DC} = 1/\lambda_{DC} = 10^6/196.847 = 5{,}080 \text{ hr}$$

The predicted Mean-Time-Between-Failures for the AC Drive ($MTBF_{AC}$) is therefore:

$$MTBF_{AC} = 1/\lambda_{AC} = 10^6/42.712 = 23{,}413 \text{ hr}$$

It would be informative to compare the DC Controller MTBF and the AC Controller MTBF, especially since the Regenerative AC Drive and the Regenerative DC Drive have identical numbers of SCR Thyristors and supporting parts in the main power rectifiers, even though the two systems have different functional tasks. Unfortunately, there is still not sufficient vendor-supplied, detailed parts data, particularly on the supporting low-power printed circuit boards in the AC Controller to support a more definitive analysis of either the standard AC industrial design or an upgraded military version. Whenever this data is furnished by vendors, it is conceivable that the difference between the AC and the DC Controller failure rates may become vanishingly small resulting in the motor failure rates alone determining which system has the greater MTBF, since the failure rates of the remaining components are identical for both the AC and the DC systems.

APPENDIX E

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